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Comparative Analysis of Sediment Production in Two Partially Harvested Watersheds in Coastal British Columbia

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Cover photo: Looking down the main valley of the Tsitika River watershed,on northeastern Vancouver Island, British Columbia. Lower Russell Creek is in the foreground.

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ABSTRACT

An on-going sediment research project has been underway in the Tsitika River watershed on northeastern Vancouver Island, British Columbia since the early 1990s. Part of the program studied sediment production during storms in two sub-basins, Catherine Creek and Russell Creek, which are two typical Coastal British Columbia streams. However, the two creek basins differ in terms of bedrock lithology, basin morphology, and harvesting history. This report presents a comparative analysis of the sediment-production characteristics of the two sub-basins from November 1991 to December 1998. Results of this analysis provide some insight into the roles of various factors, including forestry-related activities, in controlling the production and transport of suspended sediment. The results of the study provide important insights into watershed management, how to interpret Coastal Watershed Assessment Procedure (CWAP) data, and forest management implications regarding construction and use of forestry roads on highly erodible bedrock types. With further development, this research could lead to a regional approach to characterizing sediment yields from specific morphological/lithological terrain types.

KEYWORDS

forestry, forest management, hydrology, streams, sediment, sediment budget, sediment production, sediment yield, forestry roads, Vancouver Forest Region, British Columbia

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INTRODUCTION

Sediment production in creeks and rivers in Coastal British Columbia is a natural process, and the subject of ongoing research in the Vancouver Forest Region and elsewhere in the province. One of the most important issues related to this research is the effect of forest harvesting and related activities on the sediment budget of creeks.

In an effort to understand sediment-production processes, the Tsitika River Sediment Monitoring Program was initiated in 1991. Part of the program studied sediment production during storms in two sub-basins, Catherine Creek and Russell Creek, which are two typical Coastal British Columbia streams. This report presents a comparative analysis of the sediment-production characteristics of the two sub-basins from November 1991 to December 1998. Results of this analysis provide some insight into the roles of various factors, including forestry-related activities, in controlling production and transport of suspended sediment.

In support of that research, stream gauging sites were established on Russell and Catherine Creeks in November 1991, where streamflow, turbidity, and suspended sediment concentration (SSC) are measured. Starting in 1994, the stream gauge network in Russell Creek was expanded to eventually include four additional gauges at sites upstream of the original gauge. This network in Russell Creek has supported the development of a sediment-budget model that has been used to determine the relative contribution of different types of sediment sources to the sediment yield of that watershed (Hudson 2001b). The ongoing monitoring of Catherine Creek before and after development will be used to infer the extent of any changes in sediment production attributable to forest harvesting.

Prior Research in the Tsitika River Watershed

Prior studies in the Tsitika River watershed include a comparison of storm-based sediment yields from Catherine Creek and Russell Creeks (Hudson and Sterling 1998). Bedrock lithology was identified as the primary factor influencing sediment production. Catherine Creek was found to yield over 5.5 times as much sediment as Russell Creek, in spite of the fact that at the time, Catherine Creek was unharvested while Russell Creek was roaded and harvested over 25% of its area. The difference was attributed to the predominant basaltic lithology of Catherine Creek compared to the more resistant granitic bedrock that underlies the lower portion of Russell Creek. Based on a historic survey of debris flow fans, Sterling (1997) found that basaltic bedrock areas in the Tsitika River watershed produced over 6 times more debris torrents per unit area than did the granitic bedrock areas. This ratio agrees with that of storm-based sediment yields, suggesting that debris flow deposits might be the primary sediment source in Catherine Creek.

Using a detailed sediment-budget approach, Hudson (2001b) found that roads contributed between 0 and 23% of the sediment production during storms at Russell Creek, depending on storm size (e.g., 15% for a 50-mm storm). The sediment was derived from erosion of road surfaces, cut-and-fill slopes, and ditches. The relative contribution from roads increases with storm size, but is reduced overall by the buffering effect of the valley flat. On the average, the yield of sediment produced by roads as measured at the source is 3.4 times the yield as delivered to the main channel. In other words, only 30% of the sediment produced from road sources makes it to the main channel during a storm; 70% of the sediment is absorbed by the valley flat.

Background Literature

The literature has reported that, during periods of heavy road use, sediment yield from forestry roads can increase by one order of magnitude. Reid (1981) and Reid and Dunne (1984) report that sediment production from forestry road surfaces during periods of heavy use is one order of magnitude higher than during periods of moderate use or temporary non-use, which is in turn one order of magnitude higher than light-use roads. Thus, sediment yields from road surfaces span two orders of magnitude, depending on log-truck traffic volumes. The increased sediment yield consists mostly of fine material (silt and clay) that is forced to the road surface by compaction due to the weight of the log-hauling trucks, and may also include some sandy binder material (Reid 1981). Coker et al. (1993) observed sediment pulses generated from road surfaces due to the passage of individual trucks during simulated rainfall. Peak sediment concentration after a truck pass was 7 to 15 times background levels depending on the parent material on which the road was constructed. They projected an annual yield of sediment from road surfaces during periods of heavy use of 5.6 times the level during non-use periods. Nistor and Rood (1999) observed that road segments with a steep gradient (15%) generated about 10 times as much fine sediment as low-gradient (4%) road segments. Sediment production from road surfaces was also affected by road-maintenance activities. After fine material from ditches was spread on the road surface, high SSC levels persisted for at least six weeks until fine material was gradually eroded away by successive rainfall events.

Order of magnitude increases in sediment generation are also widely reported to occur as a result of road construction. The increase in sediment yield due to road construction is longer-lived than that due to truck traffic because the level of disturbance is greater. Anderson and Potts (1988) measured a 10-fold increase in sediment yield from a 0.7 km^2 section of watershed on hard meta-sedimentary bedrock after the construction of 2.5 km of road, compared to the yield from the same area prior to the construction activity. The elevated yield persisted for the whole season during which the construction activity took place, and returned to near-background levels the following year. Note that the increased yield applied to the whole watershed area as opposed to the road alone. Megahan et al. (1986) observed greatly accelerated erosion rates from newly constructed roads on granitic terrain. For the year in which the construction was done, annual sediment yield from three study creeks increased an average of 7.5 times compared to pre-construction levels and to a control creek, as measured at the basin outlet. Road density was about 1.9 km/km^2, and road gradients ranged from 2.0 to 10.7% with a mean gradient of about 7%.

Beschta (1978) noted watershed scale increases in suspended sediment yield in the year following road construction that depended on road location. At Alsea Watershed in the Oregon Coast Range, a 150% increase in yield occurred in Deer Creek as a result of mid-slope roads over 4% of the watershed. Ridgetop roads amounting to 5% of the watershed area of Needle Branch caused a 100% increase in yield in the year following construction. Subsequent to that, there was a 5-fold increase in sediment yield from Needle Branch due to clearcut harvesting of 83% of the watershed area followed by slash burning. Five years later, increased sediment yields persisted, but those increases were attributed to increased streamflow rather than to increased SSC, because sediment yield is the product of streamflow and SSC. In 1970–71, the average yield increased 120% in response to a 26% increase in streamflow, with no significant increase in SSC.

STUDY AREA

General Background, Tsitika River Watershed

The 400 km^2-Tsitika watershed is located on the northeast coast of Vancouver Island (Figure 1). The Tsitika watershed has a moist, cool climate with abundant rainfall and snowfall, and mild winter temperatures. Most of the precipitation over the study area falls during winter and is associated with the passage of frontal rainstorms embedded in the generally south-westerly circulation; over 70% of the annual precipitation falls from October to March. A large batholith of granitic Island Intrusives underlies the upper 49.2% of the watershed. The lower 50.8% of the watershed is underlain by the extrusive or basaltic Karmutsen Formation (Figure 1). These basaltic rocks are typically weak and easily eroded, and the igneous rocks are typically hard and resistant.

In the Tsitika River watershed, surficial materials consist primarily of glacial till, colluvium, and alluvium among large areas of exposed bedrock. Extensive mantles of glacial till cover middle and lower slopes in the whole watershed. Texture of surficial materials in the Tsitika watershed varies with underlying bedrock type. Upper landscapes of the Karmutsen areas are dominated by shallow sandy/clayey textured colluvium and glacial till. Mid-slope positions of the Karmutsen areas generally contain either shallow rubbly textured colluvium or shallow to moderately deep clayey glacial till; deeper till deposits dominate lower landscape positions (Jungen and Lewis 1978). The colluvial matrix is more silty on slopes derived from volcanic bedrock (Roemer 1972). Upper landscapes of the Intrusive areas of the watershed are dominated by shallow, sandy-textured colluvium and glacial till. Mid-slope landscapes in the Intrusive areas are usually occupied by shallow sandy till deposits.

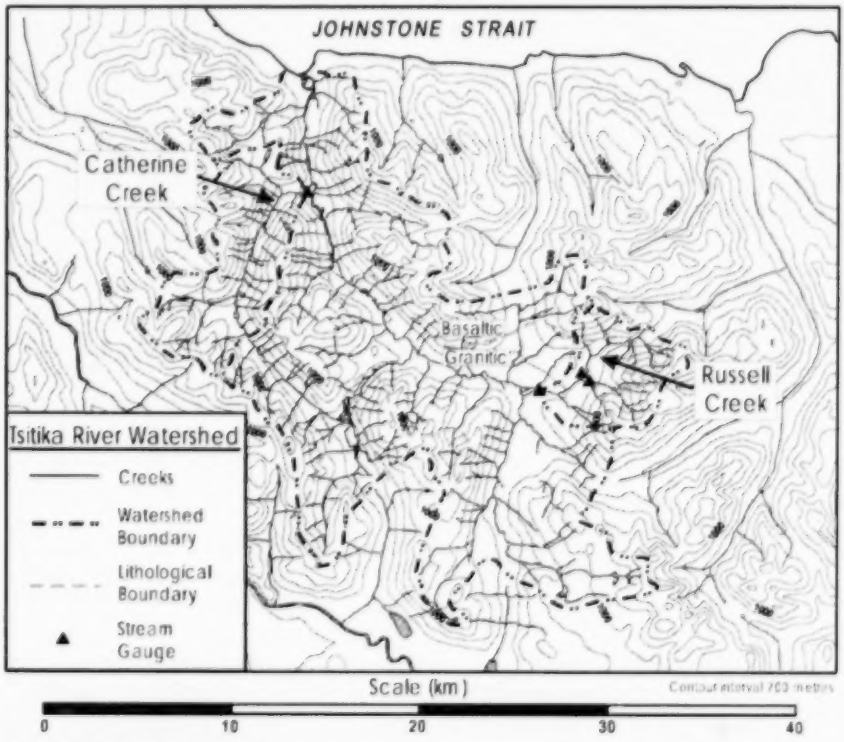

Figure 1. Map of the Tsitika River watershed.

In the Intrusive areas, residue from prolonged physical and chemical weathering provides a coarse-textured, acid parent material (Jungen and Lewis 1978).

The grain-size distribution of stream sediments can be expected to reflect the nature of the parent material as well as the hydraulic characteristics of the streams. Stream channels in the Tsitika River Watershed are generally too steep for fines to be deposited in the channel beds. Thus, while the soils on the Karmutsen formation tend to be finer textured that those on the Island Intrusive formation, this is not reflected in the grain-size distribution of channel sediments. Instead, the grain-size distribution of channel sediments appears to be related to the erodibility of the parent material, with the result that there is a higher sand content in channels on Karmutsen terrain. Streams on basaltic terrain tend to have higher gradients than those on granitic terrain, allowing the former to transport a larger proportion of sand. Duncan and Ward (1985) report similar findings in comparing streams on basaltic terrain with those on terrain with siltstone bedrock.

Catherine Creek: Morphology, Monitoring, and Forest Harvesting History

Catherine Creek (Figure 2) is dominated entirely by the basaltic Karmutsen formation. Valley sides are steep, and hillside tributaries are mostly first- and second-order gullies. A few of the larger tributaries are third order. An upper bowl contains three third-order tributaries that converge to form the main fourth-order channel. Debris flows, both recent and re-vegetated were found along the length of the watershed, as well as slope failures, both natural and harvesting related (Figure 3). Because there is no valley flat adjacent to the stream, these features are directly connected to the main channel. Introduced sediments are stored directly in the channel system. Mean channel gradient is 6% (Table 1).

Forest harvesting began in Catherine Creek in 1992. By the end of 1996, harvested area totaled 215 ha, or 4.6% of the watershed area. Road length was 19.3 km. In 1997 and 1998, 89.3 ha and 40.3 ha of land were harvested, bringing the proportion of the harvested watershed to 7.5% at the end of 1998, with approximately 27 km of road (Horel 1997). By the end of the year 2000, an additional 135.7 ha were harvested for a final proportion of 10.4% with 34.1 km of roads (Figure 2).

Monitoring of streamflow began in November 1991. Turbidity and suspended sediment concentration (SSC) were monitored continuously from November 1991 until November 1992, providing data on a total of 28 storm events. After that, turbidity and SSC monitoring became sporadic, such that only four events were effectively monitored in 1993-94. Continuous turbidity and SSC monitoring resumed again in January 1997. Thus, the harvesting history and the discontinuous nature of the monitoring result in two distinct periods in the data record at Catherine Creek: a pre-harvesting period (Period 1) from 1991-92, and a post-development period (Period 2) from 1997-99 during which sediment production during storms was monitored in conjunction with ongoing development.

Russell Creek and its Sub-Basins: Morphology, Monitoring, and Forest Harvesting History

In contrast to Catherine Creek, Russell Creek (Figure 4) is underlain by the Island Intrusive formation over the lower half of its area, with the upper slopes underlain by the Karmutsen formation. On steep slopes between the Karmutsen and Island Intrusive formations there is also a narrow transition zone where basaltic surficial material covers the granitic bedrock. A broad valley flat in the middle of the main valley buffers the channel from coarse sediments generated by debris flows and landslides (Figure 5). Thus, the largest sediment sources tend to be disconnected from the main channel. Russell Creek is a fourth-order channel with two third-order tributaries: Stephanie Creek and Russell Creek above Stephanie Confluence. A third sub-basin can be defined as lower Russell, the residual area below the Confluence (Table 1). The three sub-basins have different morphological characteristics, which serve as a basis for comparing sediment yields to provide insight on how morphological factors govern suspended sediment production and transport. Similarity ratios were calculated following the method given by Hogan (1991, Table 1b). In particular, note that Stephanie Creek is morphologically similar to Catherine Creek. About 65% of the sediment production in Russell Creek is derived from Stephanie Creek (Hudson 2001).

As of 1998, a total of 978 ha, or 31%, of the Russell Creek area had been harvested with a total road length of 53.6 km (Figure 4). Russell Creek remained relatively unchanged from 1991 to 1998 in terms of harvesting development. Harvesting proceeded at a fairly constant rate from 1980 to 1991, after which there was a break in development until 1995, with the exception of one 9.5-ha block that was harvested in 1993.

Because older blocks regenerate concurrently with ongoing harvesting, equivalent clearcut area (ECA) is less than the cumulative area harvested. ECA over time was calculated using a method described by Hudson (2000), based on measurements of stand heights in regenerating openings. As a result of the break in harvesting, peak ECA occurred in 1992 at about 20%, and declined to less than 16% by 1999 (Figure 6, upper graph). This recovery caused a reduction in peak flows in relation to storm rainfall. The rainfall parameter that correlated best with peak flow was R_{12} (Figure 6, lower graph).

There was also a gap in suspended sediment monitoring from December 1992 to April 1996, with the exception of a single event that was monitored in October 1994. As a result, Periods 1 and 2, as defined above for Catherine Creek, also correspond to two distinct phases in the development and subsequent recovery of Russell Creek, except that the trend from Period 1 to Period 2 is opposite.

METHODS

Stream and Rain Gauging

Streamflow, turbidity, and SSC were monitored at four gauging sites (Table 2). The main stream-gauging sites at Russell and

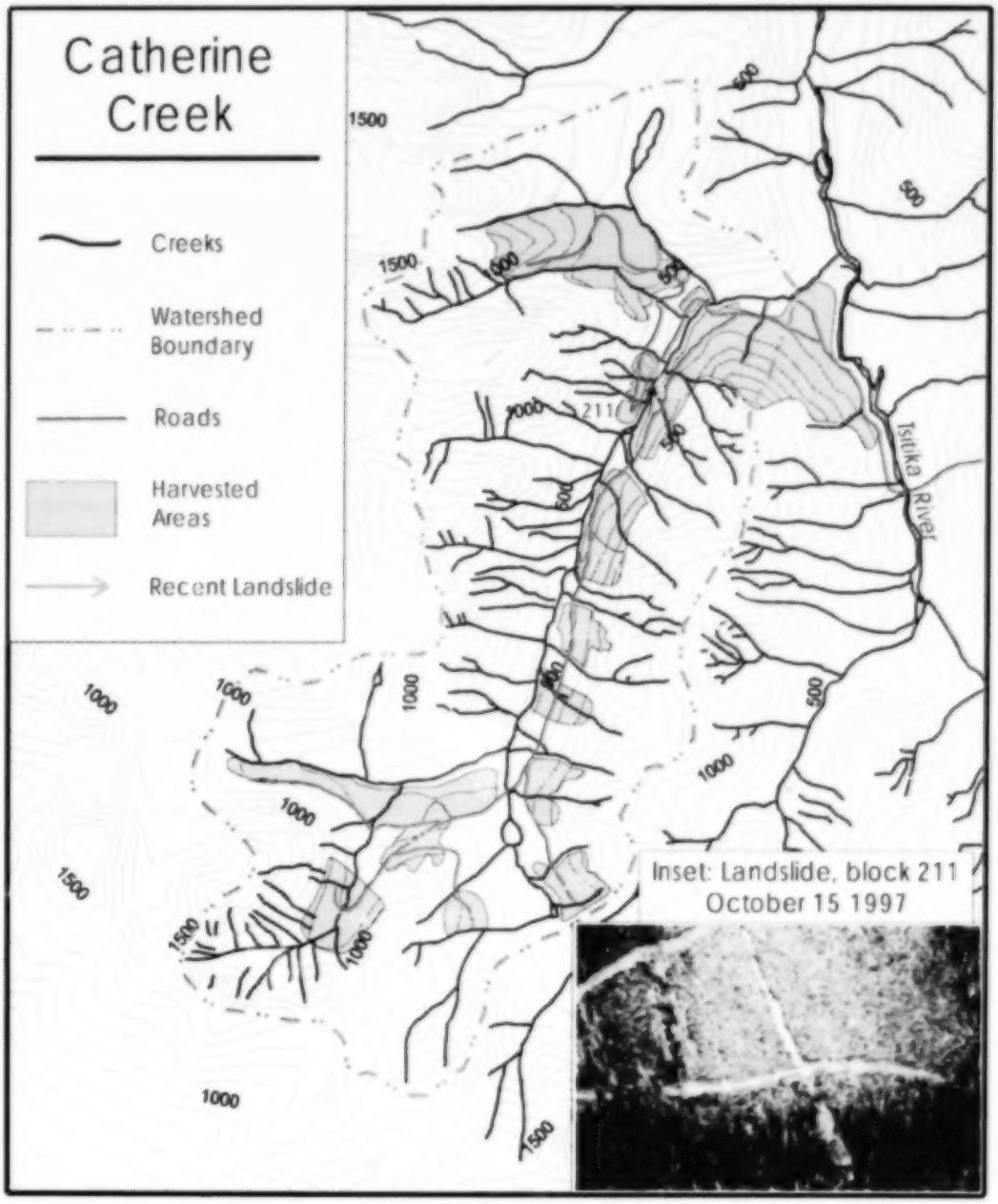

Figure 2. Map of Catherine Creek.
Figure 3, inset. Road-related landslide. Photo courtesy of Scott Cosman.

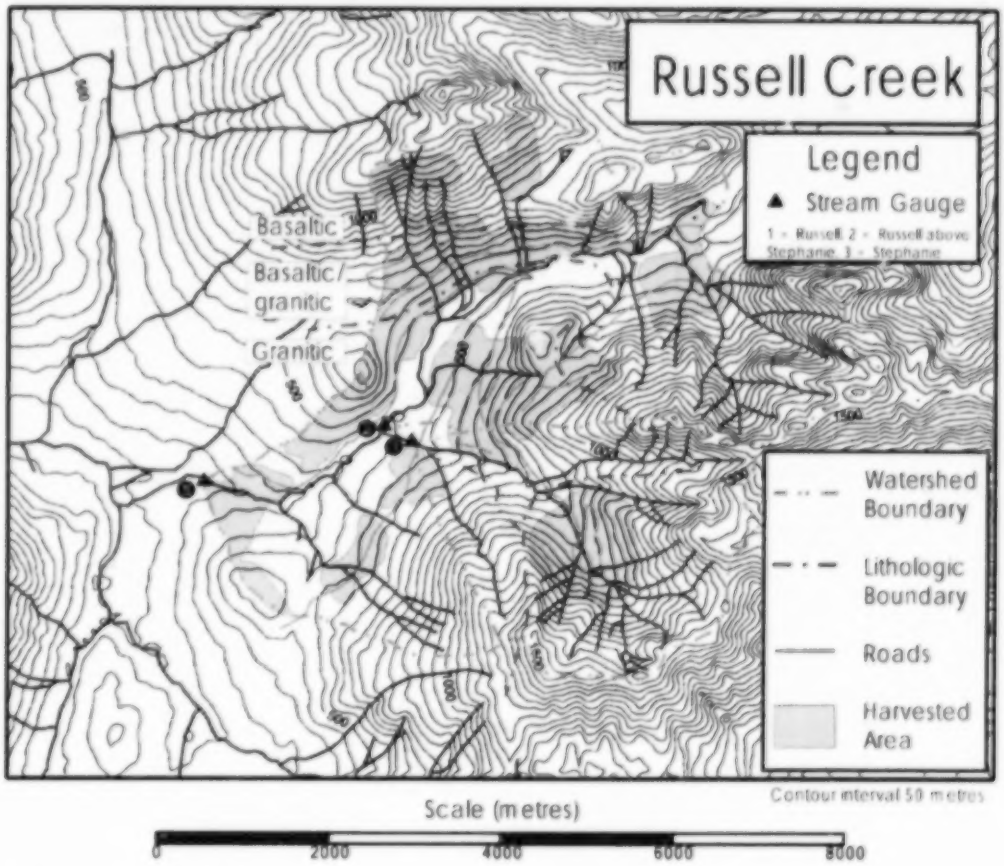

Figure 4. Map of Russell Creek.

Catherine Creeks were installed in November 1991, and operated by Water Survey of Canada (WSC) to their standards (Figure 1). Additional gauging sites were established at Stephanie Creek in the summer of 1994, and at Russell Creek above Stephanie Confluence in the fall of 1996, and these were operated by the Research Section of the Vancouver Forest Region, BC Ministry of Forests (BCMOF). Streamflow was rated using a combination of current metering and salt dilution. Both methods produced comparable results. In the summer of 1997, the operation of Russell Main and Catherine Creek gauging sites was split between WSC and the BCMOF whereby the hydrometric work was done by WSC, and the sediment/turbidity monitoring and data logger maintenance was handled by the BCMOF.

At this time, the data collection system was changed (Table 2). The high-resolution data logger was found to be a more suitable match for the OBS sensors, since the poor resolution of the original data loggers was found to result in a general lack of precision in the turbidity measurements (Hudson and Sterling 1998).

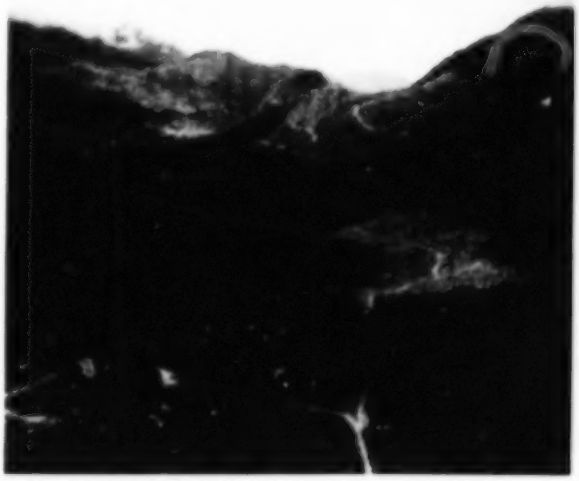

Figure 5. Russell Creek.

Table 1a. Characteristics of Catherine Creek and sub-basins of Russell Creek.

		Russell Creek		
Factor	**Catherine Creek**	**Lower Russell**	**Stephanie**	**Russell above Stephanie**
Area (km^2)	46.0	6.2	8.6	16.0
Elevation range (m)	92-1695	265-1300	500-1715	450-1600
Median elevation (m)	905	499	1118	800
Average land slope (%)	53	26	53	52
Form factor	0.33	(0.78)[a]	0.54	0.34
Lithology				
Proportion basaltic (%)	100	0	65	63
Proportion basaltic/granitic (%)	0	0	5	10
Effective proportion of basaltic (%)	100	(1)[a]	70	73
Proportion granitic (%)	0	100	30	27
Channel network				
Order at gauge	4	4	3	3
Channel gradient at gauge (%)	4	3.1	8.5	3.6
Lower channel gradient (%)	6	5.0	17	3.1
Mid channel gradient (%)	6	8	14	1.2
Drainage density	2.96	1.22	2.69	2.67
Bifurcation ratio	5.33	(1.58)[a]	4.58	3.41
Connectivity of sediment sources[b]	Connected	Connected	Connected	Buffered

[a] Values used to determine similarity ratios, although these are actually not applicable because Lower Russell is a residual area.
[b] To calculate similarity, Connected = 2, Buffered = 1.

Table 1b. Similarity ratios: $S.R. = \sum \sqrt{\left[X_{i1} / X_{i2} - 1 \right]^2}$ where X_1 and X_2 represent the value of factor i for basins 1 and 2 for which the comparison is made.

Sub-basin	**Catherine**	**Stephanie**	**Russell above Stephanie**
Stephanie	8.52		
Russell above Stephanie	10.33	19.55	
Lower Russell	113.3	81.42	81.15

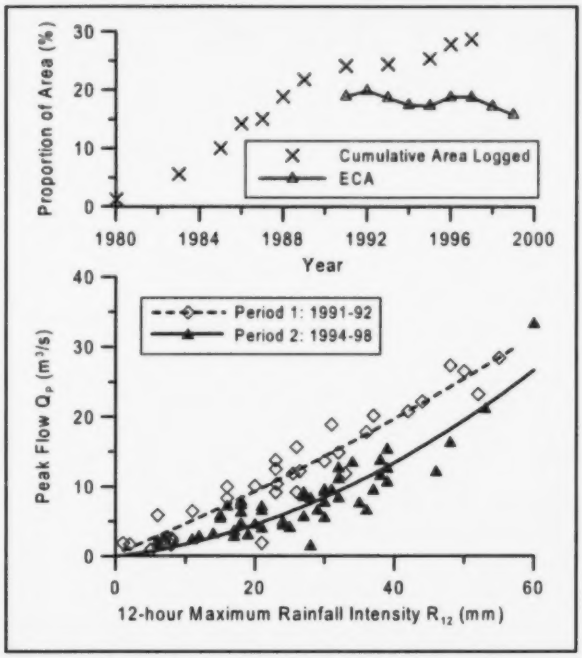

Figure 6. The effect of forest harvesting and subsequent hydrologic recovery on peak flows at Russell Creek.

Samples were recovered from the automatic sampler and analyzed for total suspended sediment concentration and, if possible, for grain-size distribution. From 1991-97, samples were analyzed at labs operated by WSC. In the fall of 1998, the analysis was done by the field crew, using the same methods, with portable lab equipment set up at the temporary home of the lead contractor. The purpose of the automatic sample collection was to field calibrate the turbidity readings, and to verify whether the turbidity readings represented actual sediment production, and thereby assist in interpretation of the data.

Rainfall was measured near each of the stream gauging sites, using a tipping bucket rain gauge with a 1-mm resolution connected to a data logger. Total rainfall was recorded every five minutes at Catherine Creek and Russell Main. At upper Stephanie Creek, rainfall and total precipitation were measured by a combination of a tipping bucket gauge and a standpipe gauge with a log interval of 15 minutes.

Data Interpretation

Continuous records of SSC were derived from turbidity readings, using calibration equations derived from suspended-sediment samples and corresponding in-stream turbidity readings. A set of calibration equations was developed for each gauging site. The interpretation of turbidity and SSC data followed the methods described by Hudson (2001a) that were developed from data collected at Russell and Stephanie Creeks. A summary of

Table 2. Monitoring systems used by time period.

Area	Period 1	Period 2
Russell/Catherine		
Stage	Site feed with mercury manometer.	Site feed with H350 lite benchtop transducer (range of 0-10.5 m), recorded by 16-bit data logger.
Turbidity	OBS-3 sensor, run continuously.	OBS-3 sensor read by same 16-bit data logger.
Data collection	Stage: Stevens A35 chart recorder. Turbidity: 8-bit data logger (turbidity) programmed to 15-min log interval.	Stage and turbidity: 16-bit data logger recording minutes, mean, and max turbidity on a 5-min interval.
SSC sampling	ISCO 3700 automatic sampler, activated by data logger based on turbidity thresholds, or programmed on time basis.	ISCO 3700 automatic sampler, activated by data logger based on pre-determined changes in stage, or programmed on time basis.
Stephanie/Confluence		
Stage	n.a.	Keller submersible transducer (range of 0-3.5 m).
Turbidity, data collection, sampling		Same as above.
Meteorology	Rain (tipping bucket) and temperature at Russell and Catherine near stream gauge.	Same as Period 1, but including total precipitation, rain, TGH, wind at upper Stephanie, and upper Russell.

that method and its application to Catherine Creek is given in Appendix A.

For each storm, total suspended sediment yield was calculated for each site that was monitored. A storm is defined as a period of continuous rainfall and the associated runoff that it produces. An individual storm starts at the initial rise of the hydrograph at the onset of rainfall, and ends when the hydrograph begins to rise again in response to the next rainfall or snowmelt event. Suspended sediment yield (Ys) is calculated as the product of the suspended sediment concentration (SSC) and the mean streamflow or discharge (Q), as follows:

$$Ys = \frac{SSC \cdot Q \cdot I}{1000} \qquad (1)$$

where

Ys is in units of kg,

SSC is in mg/L,

Q is in m^3/s, and

I is the interval in seconds.

This gives the total mass of suspended sediment transported over a single interval. The interval is either 5 or 15 minutes, depending on the data logger program. Summing the interval yields over the duration of a storm gives the total sediment yield for that storm.

The rainfall data were processed to give maximum intensities at 1- , 3- , 6- , 12- , and 24-h durations, and total daily rainfall. A running total representing each duration was calculated from the continuous data, and the maximum intensity of each duration was selected for each storm. Total daily rainfall was calculated as the total rainfall for each discrete 24-h period.

Data Analysis

A total of 98 storms with measured sediment yield, rainfall, and streamflow have been identified between November 1991 and January 1999, although sediment yield was not measured at every site during every storm (Table 3).

Hudson and Sterling (1998) characterized suspended sediment production and transport during storms according to two parameters: total suspended sediment yield, and peak SSC. They found linear relationships between the logarithms of both sediment yield and peak SSC and either peak flow or rainfall intensity for Russell and Catherine Creeks. Therefore, the sediment yield and peak SSC for each storm were log transformed and correlated with hydrological parameters including peak flow and antecedent base flow in m^3/s; total rainfall; and maximum 1- , 3- , 6- , 12- , and 24-h rainfall intensities for the storm in mm.

Results of this analysis revealed a minimum Pearson correlation coefficient between the log-transformed sediment yield ($\ln(Y_s)$) and peak streamflow(Q_p) of 0.817; $\ln(Y_s)$ was best correlated with either the 12-h maximum (R_{12}) or the 24-h maximum (R_{24}) rainfall intensity. Q_p and R_{24} were well correlated at Russell Creek, ($r = 0.92$ for Period 1) but only weakly correlated at Catherine Creek ($r = 0.73$). The logarithm of the peak SSC correlates best with R_{12} at Russell Creek and with Q_p at Catherine Creek, although the correlation in both cases is weak ($r = 0.80$ and 0.66 respectively).

As a preliminary step in identifying a predictive model of sediment yield during storms, a combination of stepwise regression and best-subsets regression was used (Minitab Inc. 1995). The stepwise regression gave a preliminary idea of the best set of variables to enter into a model of suspended sediment yield at a given site, and the best-subsets regression was used to select models that were similar from site to site, wherever possible.

Best-subsets regression was also used in some instances to select models that made sense from a physical standpoint, as opposed to purely statistical. The resulting relationships were used to investigate differences in the creeks' sediment-production characteristics. Regression-comparison analysis (Kozak 1970) was used to investigate similarity of regression relationships between sites and between different time periods at the same site. Using these methods, patterns of spatial and temporal variability in sediment-production characteristics were investigated relative to watershed morphology, lithology, and harvesting activity.

RESULTS

Temporal changes in sediment yield at Catherine Creek were investigated by comparing the sediment-yield model from Period 1 to that of Period 2, to examine the potential effects of forest development activities on sediment yield and to investigate reasons for any apparent changes in yield. A similar analysis was conducted for Russell Creek. This analysis was followed by comparison between Catherine Creek and sub-basins of Russell Creek to investigate the role of basin lithology and morphology in controlling sediment yield.

Temporal Patterns in Sediment Yield

Catherine Creek, Pre- and Post-Harvesting

Sediment production during storms at Catherine Creek was found to correlate best with peak streamflow (Q_p) and either the 12-h or the 24-h maximum storm rainfall intensity (R_{12} or R_{24}).

For Period 1, results of the model identification process indicated that $\ln(Y_s)$ was related to Q_p and R_{24}. The regression equation was plotted with a 95% prediction interval (Figure 7). (The regression line incorporates R_{24} in the form of a linear relationship between R_{24} and Q_p). When storm sediment yields from Period 2 are plotted on the same graph, it is apparent that two distinct classes of events occurred in Period 2. There was a group of events in the fall of 1997 that had elevated sediment yields compared to those of Period 1. That is, the yields fell above the upper prediction limit, indicating that their sediment

Table 3a. Storm characteristics and suspended sediment yields for Russell and Catherine Creeks.

Date	Russell Main				Catherine Creek				Yield Period
	R12 (mm)	R24 (mm)	Peak flow (m^3/s)	SS yield (kg)	R12 (mm)	R24 (mm)	Peak flow (m^3/s)	SS yield (kg)	
11/7/91	23	31	11.300	7 783					1
11/11/91	26	36	13.200	9 028					1
11/15/91	42	58	21.700	27 967	44	62	29.950	121 869	1
11/19/91	58	80	32.500	194 350	61	86	35.200	638 940	1
11/24/91	25	35	13.900	4 140	27	37	26.400	19 457	1
11/28/91	8	10	4.270				7.110	6 264	1
12/1/91	8	9	4.210	59			9.310	505	1
12/3/91	16	21	12.500	1 287	17	20	17.100	8 023	1
12/5/91	30	42	18.400	5 891	29	42	25.700	35 166	1
12/8/91	26	31	21.100	12 400	20	24	25.800	15 512	1
12/10/91	17	28			18	30	10.700	3 976	1
12/21/91	21	25	2.780						1
12/25/91	44	65	24.100	21 644	45	62	34.500	89 303	1
12/31/91	55	73	30.400	65 063	56	74	47.246	283 856	1
1/9/92	48	71	28.000	32 812	49	72	43.500	462 305	1
1/14/92	32	41	16.600	5 427	33	42	24.500	30 487	1
1/22/92	36	51	20.600	4 421	37	52	15.900	1 807	1
1/25/92					11	20	15.900		1
1/27/92	11	20	13.600	1 132					1
1/29/92	50	57	33.600	67 506	51	58	53.500	474 848	1
1/31/92	23	36	22.000	5 847	23	37	15.000	5 321	1
2/2/92	52	75	30.200	43 400	53	77	28.100	134 859	1
2/13/92	8	11	3.670						1
2/21/92	33	36	12.800	5 613	29	34	6.160	2 524	1
2/24/92	6	7	8.450	114					1
3/5/92	5	6	2.620						1
3/12/92	1	1	2.710	47					1
4/2/92	2	2	2.130	18					1
4/16/92	23	28	10.400	5 316	33	40	17.200	31 537	1
4/17/92					8	14	7.380	17 955	1
4/26/92	20	24	10.100	2 527	7	9	4.920	1 214	1
4/29/92	16	24	8.340	3 005	18	25	5.810	3 961	1
6/9/92	26	37	9.230	2 540					1
9/23/92					25	29	13.100	9 855	1
9/26/92					23	25	9.950	142	1
10/31/92	31	54	18.900	14 489					1
11/3/92	23	32	13.800	494	25	38	16.400	25 304	1
11/6/92	37	54	20.200	7 525					1
11/26/92					31	39	18.700	24 797	1
11/29/92					26	34	12.800	3 782	2a
11/2/93					43	55	31.600	97 358	2a
2/28/94					37	42	41.380	134 812	2a
3/1/94					34	42	41.610	83 582	2a
3/2/94					40	54	46.600	372 837	2a
10/24/94	53	70	22.500	110 303					2a
4/4/96	60	117	34.132	297 236	60	118			2a
4/7/96	27	29	13.113	22 098	27	28			2a

continued

Table 3a, continued.

Date	Russell Main				Catherine Creek				
	R12 (mm)	R24 (mm)	Peak flow (m^3/s)	SS yield (kg)	R12 (mm)	R24 (mm)	Peak flow (m^3/s)	SS yield (kg)	Yield Period
1/29/97	37	50	9.763		45	55	46.140	443 448	2a
2/16/97	15	17			12	12			2a
3/19/97	28	35	7.419		29	38	16.200	27 127	2a
3/25/97	12	13	4.291		9	12	10.350	8 454	2a
3/29/97							11.000	26 996	2a
4/14/97	21	31	7.592		22	35			2a
4/22/97	6	6	2.889		3	3			2a
4/25/97	15	23	7.882		19	27			2a
5/4/97	36	43	9.191	11 885	42	50			2a
5/29/97	7	9	6.359	1 736	11	12			2a
6/3/97	6	10	4.782		5	8			2a
6/10/97	19	27	4.755		20	28			2a
6/16/97	25	29	6.334		23	27			2a
9/16/97	14	30	4.389		9	24			2a
9/17/97	17	28	7.490	1 152	15	23	8.848	11 112	2a
9/26/97	30	49	8.106	2 778	29	47	17.072	147 466	2b
9/28/97	11	20	5.923	971	17	19	16.115	86 278	2b
9/30/97	38	45	16.210	16 788	36	42	20.653	343 096	2b
10/1/97	27	43	12.964	11 293	35	48	23.762	574 348	2b
10/3/97	21	29	8.022	1 769	17	25	21.440	87 774	2b
10/8/97	24	24	5.866	677	22	22	8.020	53 126	2b
10/15/97	32	58	10.942	12 350	50	74	44.945	2 640 392	2b
10/26/97	27	34	7.390	3 799	24	28	23.919	10 056	2a
10/28/97	20	25	7.233	1 368	26	47	35.874	520 339	2b
10/30/97	35	47	12.660	17 289	26	47			2b
11/2/97	31	52	13.082	16 617	36	57	41.324	715 469	2b
11/5/97	32	52	14.655	13 185	28	49	33.174	357 888	2b
11/22/97	21	35	8.097	3 563	27	49			2b
11/26/97	29	45	8.766	5 240	27	47	24.509	12 036	2a
12/14/97	30	40	10.780		39	66	30.735	226 887	2b
12/16/97							26.950	32 458	2a
1/18/98	18	25	9.133	2 239					2a
2/12/98	30	48	10.850	3 191	32	51	15.200	4 406	2a
2/19/98	38	49	13.537	6 951	40	52	16.824	6 746	2a
3/12/98	18	25	8.755	1 068	19	27	18.170	21 708	2a
3/21/98			5.205	308			10.546	3 828	2a
10/8/98	18	28	5.216	685	19	30	13.792	7 838	2a
10/12/98	34	45	14.775	18 717	47	73	33.822	452 277	2a
10/16/98	24	41	6.990	638	40	53			2a
10/17/98	28	31	14.631	7 028	37	43	39.810	139 042	2a
11/12/98	48	68	17.106	18 434	55	73	39.028	319 204	2a
11/14/98	15	27	8.614	2 674	17	34	19.835	5 382	2a
11/20/98	27	41	11.194	4 863	33	56	21.914	37 386	2a
11/25/98	30	57	10.438	769					2a
12/10/98	32	43	14.027	2 758	56	64	36.792	81 760	2a
12/12/98	39	57	18.714	27 195	48	64	46.700	770 803	2a
12/15/98	18	22	11.203	2 429	17	18	14.888	12 249	2a
12/29/98	17	29	6.025	534					2a
12/31/98	16	17	10.813	1 310					2a
1/10/99	39	50	15.829	8 682	34	43	36.248	277 533	2a
1/14/99	46	74			50	71	26.320	29 040	2a

Table 3b. Storm characteristics and suspended sediment yields for sub-basins of Russell Creek.

Date	Rain1		Stephanie Creek				Russell above Stephanie		Lower Russell	
	R12 (mm)	R24 (mm)	R12 (mm)	R24 (mm)	Qp (m^3/s)	SS yield (kg)	Qp (m^3/s)	SS yield (kg)	Qp ($m^3/s/km^2$)	SS yield (kg)
4/4/96	60	117	54	101	6.009	171 280	11.315	26 390	2.694	96 893
4/7/96	27	29	23	24	5.991	39 354				
1/29/97	37	50	42	55	5.217	18 294	9.216	7 867		
2/16/97	15	17	15	17	3.300	4 303				
3/19/97	28	35	40	63	4.413	16 114				
3/25/97	12	13	9	15	1.930	620				
4/14/97	21	31	28	41	4.926	15 777				
4/22/97	6	6	9.0	10.0	1.919	854				
4/25/97	15	23	14	23	5.257	44 692				
5/4/97	36	43	58	67	5.663	16 725	9.224	3 208		
5/29/97	7	9	16	24	4.279	7 554	4.845	367		
6/3/97	6	10	12	13	3.942	1 302				
6/10/97	19	27	15	21	3.633	4 957				
6/16/97	25	29	24	28	4.288	5 699				
9/26/97	30	49	31	43	2.504	982	5.831	519	0.662	1 277
9/28/97	11	20	42	43	2.125	463	4.214	258	0.154	251
9/30/97	38	45	38	55	3.463	12 754	9.179	2 555	0.572	1 479
10/1/97	27	43	14	21	3.225	8 725	8.489	1 866	0.200	702
10/3/97	21	29	22	33	2.535	1 051	5.886	464	0.276	254
10/8/97	24	24	25	26	1.524	168	4.287	207	0.204	302
10/15/97	32	58	27	50	3.158	5 513	8.252	1 453	0.887	5 383
10/26/97	27	34	20	27	2.123	2 287	4.205	447	0.170	1 065
10/28/97	20	25	28	39	2.289	921	3.886	188	0.170	259
10/30/97	35	47	37	64	3.174	12 543	6.718	2 856	0.444	1 891
11/2/97	31	52	21	42	3.151	12 345	7.165	3 302	0.443	970
11/5/97	32	52	27	44	3.198	10 047	7.075	1 997	0.702	1 142
11/22/97	21	35	27	41	2.228	1 656	4.876	716	0.159	1 191
11/26/97	29	45	27	41	2.723	2 505	5.375	948	0.572	1 788
12/14/97	30	40	24	28	2.796	3 920				
12/28/97	39	68	38	55	2.986	24 973				
1/18/98	18	25	28	40	1.394	1 055	6.629	674	0.178	509
1/23/98	29	48	48	88	2.485	12 203	7.081	1 107	0.638	
1/28/98	24	34			2.461	11 460	7.321	1 358	0.357	
2/12/98	30	48	19	21	1.347	540	5.045	674	0.714	1 978
2/19/98	38	49	47	53	2.324	3 329	6.217	785	0.801	2 837
3/12/98	18	25	13	19	1.756	1 197	4.917	397	0.334	
3/21/98			14	16	1.227	329	3.305	181	0.108	
10/8/98	18	28	14	26	1.251	78	2.733	268		
10/12/98	34	45	37	57	4.187	13 661	7.962	3 134	0.421	1 922
10/17/98	28	31	24	27	4.757	5 387	7.533	892		
11/12/98	54	68	58	59	5.730	12 888	8.414	2 621	1.176	2924
11/14/98	15	27	17	25	1.915	916	5.162	1 248	0.246	510
11/20/98	27	41	42	56	3.447	2 842	5.923	992	0.488	1 030
12/10/98	43	43	45	54	4.384	1 272	6.428	293	0.515	1 194
12/12/98	39	57	39	62	4.461	18 257	8.769	4 758	0.879	4 179
12/15/98	18	22	10	14	2.471	1 146	6.010	614	0.436	669
12/29/98	17	29	33	38	1.551	103	3.314	174	0.186	256
12/31/98	16	17	22	24	1.737	614	5.780	550	0.121	147

yields are significantly higher than expected, based on the pre-development model. These events were separated from the rest of the Period 2 events and designated as Period 2b. The rest of the Period 2 events were designated as Period 2a.

Regression comparison analysis revealed that regression of $\ln(Y_s)$ vs. Q_p for Period 2b was significantly different from that of Periods 1 and 2a, but that the regressions for Periods 1 and 2a were colinear. Therefore, a single regression equation was used to characterize Periods 1 and 2a (Figure 7). Sediment yield during storms for Periods 1 and 2a ($Ys_{1,2a}$) is related to peak streamflow (Q_p) and the 24-h maximum rainfall intensity (R_{24}) as follows:

$$\ln[Ys_{1,2a}] = 7.07 + 0.0902Q_P + 0.0265R_{24}$$

s.e. = 0.6463, R^2 = 86.5% (2)

The data points that fall above the regression line represent events that involve normal to coarse regime transitions, and the points that fall below the line represent events where the transitions do not occur (see Appendix A, and Figure 7). The latter group of events can be considered supply limited relative to the former group.

For Period 2b, sediment yield during storms (Ys_{2b}) is related to peak streamflow (Q_p) and the 12-h maximum rainfall intensity (R_{12}) as follows:

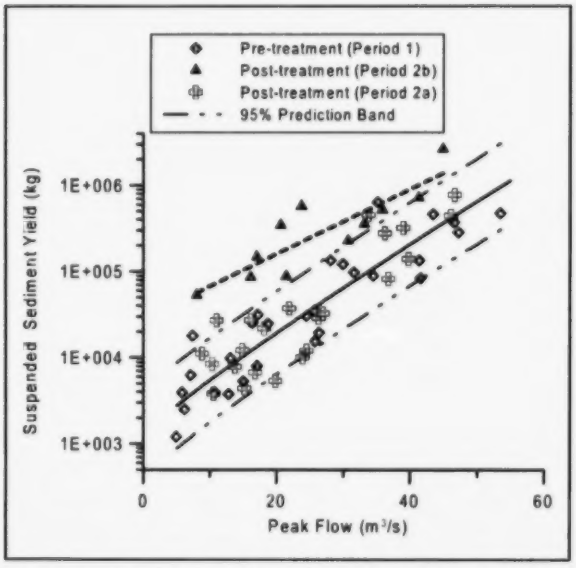

Figure 7. A predictive relationship for sediment yield at Catherine Creek as a function of peak flow and rainfall intensity for different periods.

$$\ln[Ys_{2b}] = 9.46 + 0.0563Q_P + 0.0524R_{12}$$

s.e. = 0.4350, R^2 = 85.3% (3)

All except one of the measured storm yields for Period 2b fell outside the prediction interval associated with Equation 2 (Figure 7). The Period 2a events were all similar to the supply-limited group from Period 1 in that they fell below the regression line defined by Equation 2.

Assuming that increases in suspended sediment yield during Period 2 at Catherine Creek are a consequence of forest-harvesting activity, it is then reasonable to calculate the increase in sediment yield for the storms in that period relative to those in Period 1. This is done by subtracting the yield as predicted by Equation 2 from the observed yield for each Period 2 storm to give the expected portion of yield attributed to forest development activity in units of Mg (Y_f, Table 4). A confidence interval can be calculated for Yf : the minimum and maximum excess yields are equal to the observed yield minus the upper and lower 95% prediction intervals of Equation 2, respectively. Thus the total expected excess yield attributable to forest harvesting activities in Period 2b is 4038 Mg, but could vary from 1160 to 5095 Mg. The increase in yield can also be expressed as a percentage difference between observed yield and yield as predicted by Equation 2 (Table 4).

Both quantities are related to storm size (Figure 8). Y_f increases with increasing storm intensity (lower graph), while the percent increase in yield during Period 2 is generally greater for small than large storms (upper graph). For storms with R_{24} less than 50 mm, the average increase in sediment yield was 900%; for storms of R_{24} greater than 50 mm, the increase was 590%. If the percentage increases in yield are weighted according to the magnitude of the observed yields, then the weighted average increase in yield is 770%.

Cause of Increased Sediment Yield at Catherine Creek

Two possible causes for the increased yield during Period 2 are discussed here: contributions from episodic mass-wasting events, and contributions from forest harvesting activity.

Episodic mass-wasting events that entered the channel. At Catherine Creek, at least one event is known to have involved a landslide. On or about 15 October 1997, a landslide occurred directly below the upper Mudge Main haul road that entered Catherine Creek (inset in Figure 2). The landslide was caused by "a concentrated flow of surface water that was diverted from the upper roadway into the area of the slide" (Cosman 1997). The effect of the landslide appears as a spike in suspended sediment that reached a maximum of more than 4100 mg/L of suspended sediment (Figure 9).

As with total suspended sediment yield, peak SSC is apparently affected by harvesting. For Periods 1 & 2a, and Period 2b, peak SSC is related to peak flow by Equations 7 and 8 respectively, as follows:

Table 4. Changes in sediment yield on Catherine Creek during Period 2 relative to Period 1 prediction.

Date	SS yield (kg)	Pre-harvesting prediction	Change in yield				
			Expected (Mg)	Max. (Mg)	Min. (Mg)	Expected (%)	R24 (mm)
1/29/97	443 448	272 090	171	n.a.	n.a.	63.0	55
3/19/97	27 127	16 277	11	n.a.	n.a.	66.7	38
3/25/97	8 454	3 576	5	n.a.	n.a.	136.4	12
3/29/97	26 996	46 171	-19	n.a.	n.a.	-41.5	77
9/17/97	11 112	4 570	7	n.a.	n.a.	143.1	23
9/26/97	147 466	17 161	130	143.1	107.0	759.3[a]	47
9/28/97	86 278	8 129	78	82.4	50.5	961.3[a]	19
9/30/97	343 096	32 230	311	146.8	91.5	964.5[a]	42
10/1/97	574 348	37 174	537	564.5	485.2	1 445.0[a]	48
10/3/97	87 774	11 400	76	80.1	17.7	670.0[a]	25
10/8/97	53 126	6488	47	51.8	40.2	718.9[a]	22
10/15/97	2 640 392	335 712	803	937.3	0.0	686.5[a]	74
10/26/97	10 056	19 963	-10	n.a.	n.a.	-49.6	28
10/28/97	520 339	47 820	473	477.7	127.8	988.1[a]	47
11/2/97	715 469	119 763	596	637.8	0.0	497.4[a]	57
11/5/97	357 888	45 168	313	327.7	82.3	692.3[a]	49
11/26/97	12 036	24 544	-13	n.a.	n.a.	-51.0	47
12/14/97	226 887	72 763	154	203.7	15.4	211.8[a]	66
12/16/97	32 458	17 170	15	n.a.	n.a.	89.0	29
2/12/98	4 406	17 907	-14	n.a.	n.a.	-75.4	51
2/19/98	6 746	32 235	-25	n.a.	n.a.	-79.1	52
3/12/98	21 708	10 451	11	n.a.	n.a.	107.7	27
3/21/98	3 828	2 164	2	n.a.	n.a.	76.9	
10/8/98	7 838	7 914	0	n.a.	n.a.	-1.0	30
10/12/98	452 277	139 539	313	418.4	142.2	224.1	73
10/17/98	139 042	115 190	24	71.7	0.0	20.7	43
11/12/98	319 204	306 900	12	259.1	0.0	4.0	73
11/14/98	5 382	10 321	-5	n.a.	n.a.	-47.9	34
11/20/98	37 386	33 985	3	27.0	0.0	10.0	56
12/10/98	81 760	281 952	-200	33.9	0.0	-71.0	64
12/12/98	770 803	334 720	436	623.2	0.0	130.3	64
12/15/98	12 249	7 539	5	8.8	0.0	62.5	18
1/10/99	277 533	77 384	200	n.a.	n.a.	258.6	43
1/14/99	29 040	102 880	-74	n.a.	n.a.	-71.8	71

[a] Period 2b.

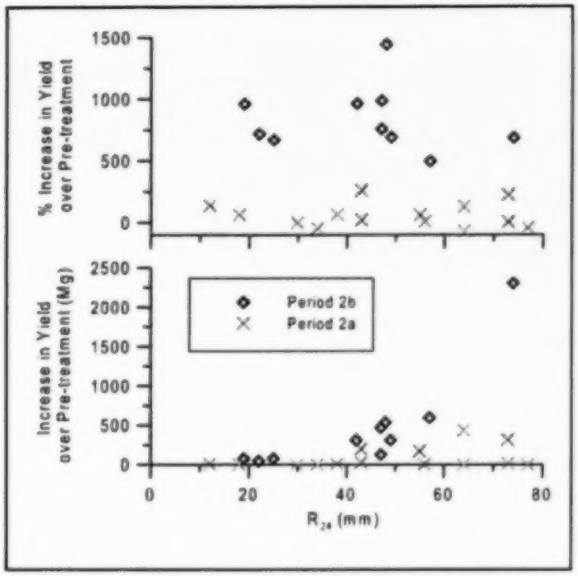

Figure 8. The percentage increase in sediment yield during storms at Catherine Creek during periods of activity relative to storm size.

$$SSC_{p(1,2a)} = 10.7e^{0.079Q_p}$$

$R^2 = 66.6\%$ (4)

$$SSC_{p(2b)} = 108.7e^{0.042Q_p}$$

$R^2 = 42.0\%$ (5)

Although the effect of forest development activities on peak SSC is less clear than that of sediment yield, nonetheless the effect of known landslides is to increase the peak SSC by 5–10 times (Figure 10). Because of the greater variability in the peak SSC vs. Qp relationship, a 90% prediction interval was used to distinguish unusual events. The peak SSC of the 15 October event lies well above the upper prediction limit of Equation 5. Similarly, the event of 30 September 1997 (Figure 11) may also have involved episodic mass wasting because peak SSC for that event is amplified by a similar factor (Figure 10). For both these events, the yield from the landslide was estimated by reconstructing hypothetical SSC hydrographs using relationships between SSC and Q for similar events, and by using different relationships for rising and falling streamflow. The resulting peak SSC was found to fall within the confidence limits of Equation 5, suggesting that these estimated SSC hydrographs are reasonable estimates of sediment production and transport due to prevailing conditions, assuming that the landslide had not occurred. In each case, the landslide more than doubled the suspended sediment yield (Table 5). In comparison, events of 30

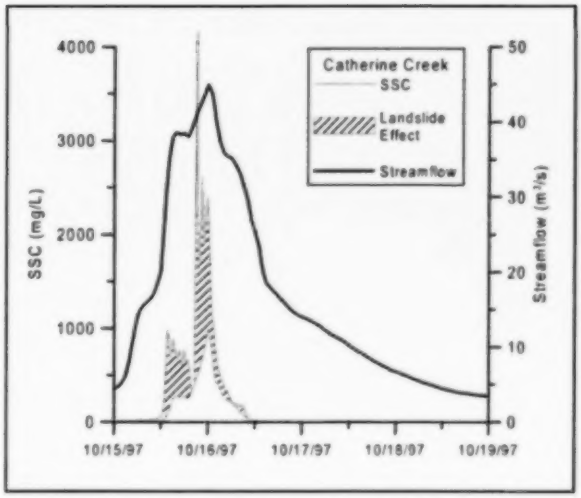

Figure 9. Catherine Creek streamflow and SSC, 15 October 1997 storm.

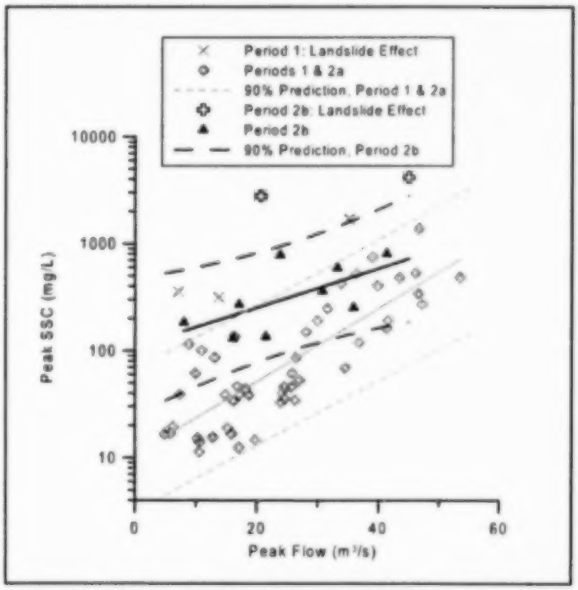

Figure 10. Relationships between peak SSC and peak flow at Catherine Creek.

January 1997 and 20 November 1998 from Period 2a (Figures 12, 13) have peak flows comparable to those of the 15 October and 30 September 1997 events, but SSC levels are much lower.

By the same reasoning described above, some events from Period 1 also appear to have involved mass wasting. One such event occurred on 19 November 1991 (Figure 14). The peak

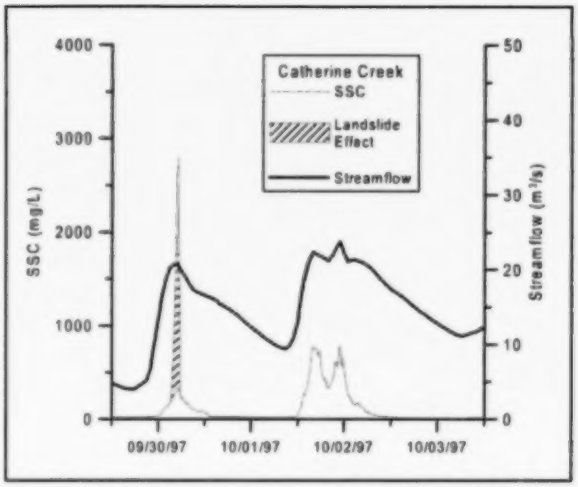

Figure 11. Catherine Creek streamflow and SSC, 30 September – 01 October 1997 storms.

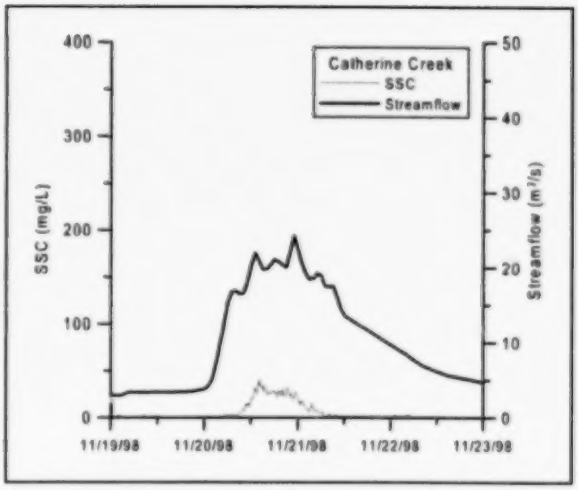

Figure 13. Catherine Creek streamflow and SSC, 20 November 1998 storm.

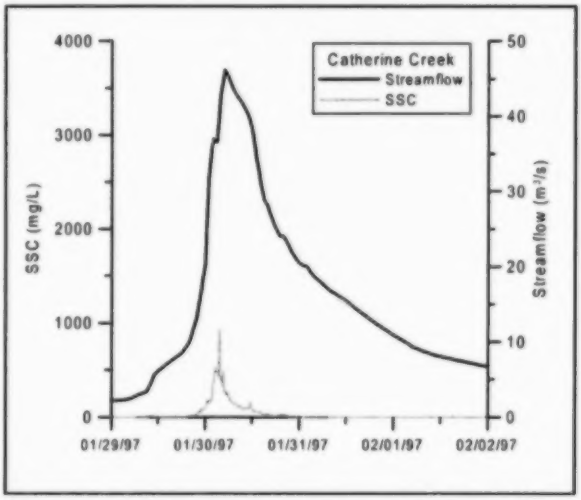

Figure 12. Catherine Creek streamflow and SSC, 30 January 1997 storm.

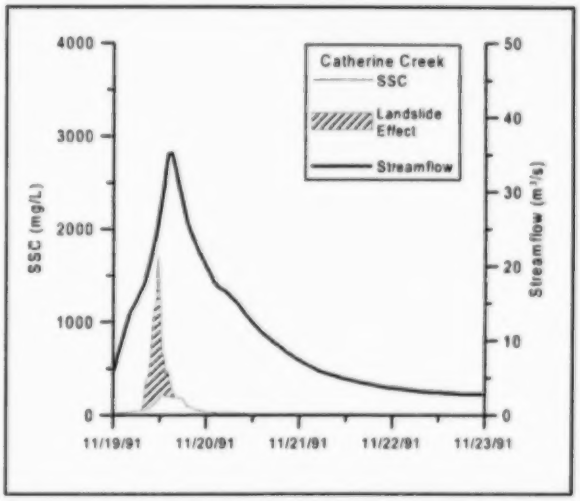

Figure 14. Catherine Creek streamflow and SSC, 19 November 1991 storm.

SSC was well above the upper 90% prediction limit of Equation 4 (Figure 10). Even though the effect of the apparent mass-wasting event was superimposed over natural background SSC levels instead of levels that are apparently affected by harvesting development (as in the above events), the effect of the landslides on sediment production is comparable (Table 5).

Road construction and use. Several lines of evidence suggest that the large increases in suspended sediment observed in the fall of 1997 are in part road related:

1. The change in the normal regime to a finer grain-size distribution (see Appendix A, Figure A2) suggests a contribution from roads in 1997–1998, where no such contribution existed in 1991–92. Roads are well known to be a major source of fine sediment (Reid and Dunne 1984).

2. Increased sediment yield on a watershed scale is consistent with road construction.

3. Sediment production returned to pre-harvesting levels in mid December 1997, and remained there for the duration

Table 5. Summary of the effects of landslides on sediment production.

Date	Peak flow (m^3/s)	Measured peak SSC (mg/L)	Estimated peak SSC without landslide effect (mg/L)	Yield 1, measured (kg)	Yield 2, LS effect removed (kg)	Ratio of Yield 1/ Yield 2
Catherine						
9/30/97	20.65	2 800.0	259.0	343 096	153 564	2.23
10/15/97	44.95	4 166.0	718.7	2 640 392	1 028 078	2.57
11/19/91	35.20	1 697.8	219.5	629 559	245 328	2.57
Russell						
10/24/94	22.50	1 061.0	116.5	115 551	6 2581	1.85
4/7/96	13.11	202.0	56.1	23 003	13 851	1.66

of the season. At that time, harvesting operations were shut down in the watershed and did not resume again until the summer of 1998. This suggested that the level of road use might be responsible for the large yields, as opposed to the actual presence of the roads.

4. There was more harvesting activity in Catherine Creek in 1997 than 1998, which could explain the high sediment yields in that year. Increased sediment yields are also indicated for the fall of 1998 at a lower level than the excess yields in 1997, which is consistent with lighter road use, or with construction of shorter sections of road.

In order to investigate this, activity reports were obtained from Weyerhaeuser (the company doing the harvesting) for 1997 and 1998, which summarized monthly road construction and timber production from Catherine Creek and other sub-basins of the Tsitika River[1]. Timber production can be used as a direct indicator of road use, as it represents the total volume of timber that was loaded onto trucks and removed from a given site in a given month. Using data in Table 4, the total expected and the total minimum monthly excess sediment yields were calculated for each month in Period 2 with a more-or-less complete record of storm sediment yields. For the events that occurred on 30 September and 15 October 1997, the yields were adjusted to remove the apparent contribution from episodic events. These monthly excess yields were summarized along with monthly timber production and road construction in Catherine Creek (Table 6). Even though the sediment source inventory is incomplete, if we assume for the time being that the excess yield is derived mostly from road construction and use, then the activity data can be used to analyze potential causes of the increased sediment yield.

Road use was weighted according to the length of road along which the logs were hauled to transport them from the setting to a point outside the watershed. The variable T_r was used to represent truck traffic (truck-km/month), calculated as the volume of timber produced in a given month, divided by an average of 40 m^3/truck and multiplied by the hauling distance. In all cases, this involved hauling along Catherine Main, since this is the only way out of the watershed. Unlike road construction, the effects of heavy road use on sediment yield are much more immediate. For example, Reid and Dunne (1984) found that sediment yield from heavily used road surfaces dropped off by an order of magnitude on weekends because no hauling takes place on weekends. Thus, the effects of road use lasted much less than one month, so there should be a direct correspondence between excess yield and road use without any treatment of the data. The excess sediment yield was correlated with road use on some but not all roads. This is because in many cases, hauling occurred at times when there was either no storm activity, or storms were not monitored for sediment production. The percentage increase in sediment yield correlated best with hauling of timber from Blocks 208 and 209 (Figure 2); these blocks involved the longest hauling distance (8.4 and 8.8 km respectively).

According to the literature, road construction is more likely than road use to result in the large yield increases observed at Catherine Creek. Increases in sediment yield, as measured at the watershed outlet, in the order of 5–10 times that of background levels, and lasting for several months after construction, have been reported. Intuitively, the magnitude of the increased yield should be related in part to the length of road constructed, or to the increase in road density. Nistor and Rood (1999) have suggested that sediment created by road disturbance gradually winnows away over a period of months due to successive rainfall events. This suggests that the effect of road construction on sediment yield can be represented by a decay function, as follows:

[1] R. Dayton, Forest Engineer, North Island Division, Weyerhaeuser, Campbell River, BC; personal communication, March 2001.

Table 6. Summary of monthly truck traffic and associated changes in sediment yield.

Date	Block number & hauling distance (no. trucks/mo.)							Total monthly road construction (m/mo.)	Effective road length (ERL_c, m)	Monthly traffic from Blocks 208 & 209 (T_p, truck-km/mo.)	Total storm rainfall for measured storms (R5i, mm)	Expected increase in yield over background due to forest harvesting (Mg)	Min. increase in yield over background due to forest harvesting (Mg)
	Block 202, 2.6 km	Block 204, 4.2 km	Block 205, 5.4 km	Block 208, 8.4 km	Block 209, 8.2 km	Block 210, 8.2 km	Block 211, 2.4 km						
Jan-97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	46.0	171.4	n.a.
Feb-97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	42.0	n.m.	n.a.
Mar-97	9.7	58.1	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	139.6	15.7	n.a.
Apr-97	1.0	27.0	60.0	0.0	0.0	0.0	649.3	0	0.0	0.0	62.1	n.m.	n.a.
May-97	0.0	0.0	97.8	0.0	0.0	0.0	706.3	0	0.0	0.0	108.5	n.m.	n.a.
Jun-97	0.0	0.0	60.5	0.0	9.7	0.0	299.8	0	0.0	79.3	50.3	n.m.	n.a.
Jul-97	0.0	0.0	20.3	0.0	97.9	0.0	366.0	413	413.0	802.6	n.a.	n.m.	n.a.
Aug-97	0.0	0.0	8.5	0.0	42.9	0.0	229.3	0	181.7	351.6	n.a.	n.m.	n.a.
Sep-97	0.0	0.0	5.1	9.5	58.7	0.0	16.0	1469	1549.0	560.9	158.5	336.3	249.0
Oct-97	0.0	0.0	0.0	67.2	0.0	0.0	0.0	50	731.5	564.1	387.1	1852.4	670.9
Nov-97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	321.9	0.0	265.6	908.4	82.3
Dec-97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	141.6	0.0	103.6	169.4	15.4
Jan-98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	62.3	0.0	125.7	0.0	0.0
Feb-98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	27.4	0.0	25.2	0.0	n.a.
Mar-98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	12.1	0.0	n.a.	12.9	n.a.
Apr-98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	5.3	0.0	n.a.	n.m.	n.a.
May-98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	2.3	0.0	n.a.	n.m.	n.a.
Jun-98	0.0	0.0	0.0	9.6	3.3	0.0	0.0	483	484.0	107.7	n.a.	n.m.	n.a.
Jul-98	0.0	0.0	0.0	5.3	73.6	97.4	0.0	0	213.0	648.0	n.a.	n.m.	n.a.
Aug-98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	93.7	0.0	208.9	n.m.	n.a.
Sep-98	0.0	0.0	0.0	87.0	0.0	0.0	0.0	450	491.2	730.8	194.6	n.m.	n.a.
Oct-98	0.0	0.0	0.0	16.8	0.0	0.0	0.0	110	326.1	141.3	180.5	336.6	142.0
Nov-98	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0	143.5	10.9	142.5	15.7	0.0
Dec-98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	63.1	0.0	114.0	440.8	0.0
Jan-99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	27.8	0.0	95.0	126.3	0.0

n.a. = not applicable. n.m. = no measurement.

where

ERL_t is the effective road length for month t,

ERL_{t-1} is the effective road length for the previous month,

C is a recession constant, and

RL_t is the length of new road constructed in month t.

A recession constant of 0.44 was found to give the best correlation between effective road length and the excess yield.

Because a relationship exists between excess sediment yield and storm rainfall (Figure 8), that variable was included in the analysis. Therefore, the variables that were considered for modeling the excess sediment yield due to road construction and use (Ys_R) included storm rainfall for all monitored storms in a given month (R_{it}), R_{24}, T_t, ERL_t and interactions between variables. The analysis identified the following regression equation:

$$Ys_R = 0.0154ERL_t \cdot R_{St} - 1.30ERL_t + 0.00065T_t \cdot R_{St} - 0.000011ERL_t \cdot T_t \cdot R_{St}$$

(s.e. = 167.2 Mg, R^2 = 94.7%) (7)

where

Ys_R is in Mg,[2]

ERL_t is in metres,

R_{it} is in mm, and

T_t is in truck-km/month.

The total expected excess yield from Period 2—derived by subtracting values predicted by Equation 2 from measured values—is 4386 Mg. Equation 7 predicts 3652 Mg of excess yield, or 83% of the former value. Since neither value is measured directly, both numbers are equally valid.

The relative contribution from road use to the excess post-development yield can be estimated from the third term of Equation 7 alone, as follows:

$$Ys_{Road-Use} = 0.00065T_t \cdot R_{St} = 217.3Mg \quad (8)$$

This suggests that an average of about 6% of the excess yield is due to road use, about 89% is due to road construction, and about 5% is due to background variability. A total of 1.975 km of new road was built during Period 2 for a new-road density of 0.065 km/km².

If the analysis is re-done using the minimum excess yields, derived from subtracting the predicted yields plus the 95% prediction limit from the observed yields, the regression analysis results in the following equation:

$$Ys_{R,min} = 21.5 + 0.00337T_t \cdot R_{St} + 0.000978ERL_t \cdot R_{St} - 0.000002ERL_t \cdot T_t \cdot R_{St}$$

(s.e. = 12.69 Mg, R^2 = 99.7%) (9)

This equation predicts a minimum of 1225 Mg of excess sediment yield compared to the 1160 Mg for Period 2 derived by subtraction as stated above. According to this scenario, 92% is derived from road use.

The total monthly mass yield of excess harvesting-related suspended sediment is primarily related to the interaction between the effective length of newly constructed road and rainfall (Figure 15, lower graph). It was difficult to find a predictive relationship in which the sediment contribution from truck traffic was non-negative. Because the contribution from road use is much less than that of road construction, the road-use contribution is hidden within the variability of the road-construction relationship. The ratio of observed yield over yield predicted by Equation 2 can be used in place of the mass of excess sediment as an indicator of the effects of road activity on sediment yield (Figure 15, upper graph). The optimum regression equation to predict that ratio uses only the interaction terms between ERL_t and T_t, and R_{it} and has an R^2 of 97.4%, but the coefficient of the road-use term in that equation is negative.

The total expected excess yield generated over a 3-month period from mid September to mid December 1997 was 3266.6 Mg, of which about 196 Mg is attributed to road use. To haul

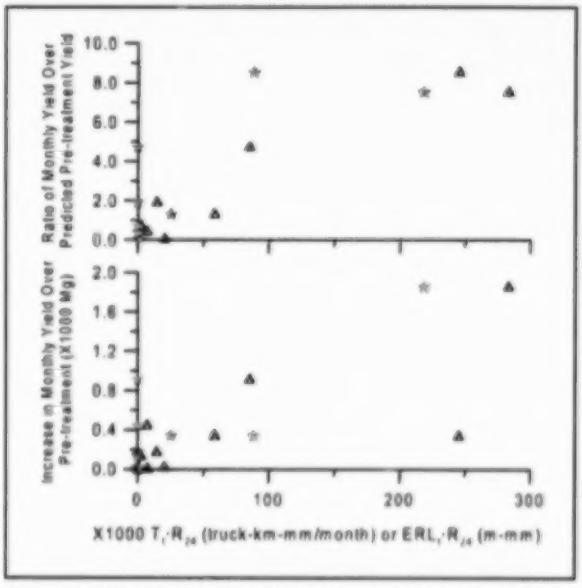

Figure 15. The Period 2 yield attributed to harvesting activity in relation to road construction (triangles) or road use (stars). The lower graph depicts the actual mass yield, while the upper graph depicts ratios of observed yield over yield predicted by Period 1 relationship.

[2] Mg = megagram. 1 megagram = 1 metric tonne, or 1000 kg.

timber from blocks 208 and 209 involves a mean haul distance of 8.6 km, thus the excess yield is 22.8 Mg/km of road. The mean gradient of the Catherine Main road is about 5%. To compare this to published values, the yield needs to be pro-rated to an annual estimate. Using the entire record of storm sediment yields at Catherine and Russell Creeks (Table 3a), it was determined that 56% of the storm-based sediment yield from 1991–1998 was derived from the period between mid September and mid December. Therefore, the sediment yield from road use derived from the expected excess yield in the fall of 1997 was about 40.7 Mg/km/y. If the minimum excess yields are used instead of the expected values, the excess yield is dominated by the road use term, resulting in 194.4 Mg/km/y of sediment derived from road use.

Log-truck traffic levels during that period were at a maximum of about 560 truck-km/month, or an average of 3.5 trips/day, which is at the upper end of the moderate-use category according to Reid and Dunne (1984). For moderate-use roads of gradient similar to Catherine Main, Reid and Dunne report sediment yields of 36 Mg/km/y. Heavily used roads produce 440 Mg/km/y. Thus, a range of 41 to 195 Mg/km/y due to road use in Catherine Creek is reasonable compared to the published values. Thus, road use amounts to between 6 and 25% of the expected excess yield.

Since this range of possible values of road-use yield seems accurate, then a minimum of 98 Mg and an expected value of 3577 Mg of sediment are derived from other sources, including erosion or mass wasting from newly built road segments, some of which were built to access the ongoing harvesting. This amounts to a potential 7.5-fold increase in sediment yield at an effective length of new road of 1.55 km, or a 2.8-fold increase, averaged over the period of active road construction, in response to a total of 3 km of newly constructed road (Table 7a).

To compare these results with published results, the mean ratio of the observed over background yield is calculated for the fall of 1997, and the fall of 1998, and compared to the results of Anderson and Potts (1987) and Megahan et al. (1986) in relation to the density of newly constructed road (Table 7b). The mean yield ratio for the fall of 1997 forms a straight line relationship with the other study results (Figure 16, upper graph). However, when a log scale is used on the X-axis, an interaction between road density and basin lithology is suggested (Figure 16, lower graph). The expected annual yield per km of new road based on pro-rating the yields during the fall of 1997 is 3.31 Mg/km/y. The upper end of the range is comparable to the results of Megahan et al. (1986). Therefore, at new-road densities comparable to those reported by Anderson and Potts (1987) or Megahan et al. (1986), the sediment yield due to road construction on basaltic terrain could be substantially higher than what was observed.

The above analysis is based on the assumption that the entire excess sediment yield from Period 2b was derived from roads. The recession constant for use in Equation 6 was based on this assumption; there is no a-priori estimate of what constitutes a reasonable recession constant. There are no published values in the literature. However, since the sediment source inventory for Catherine Creek is incomplete, other potential sources of sediment that could have contributed to the increased sediment yield in Period 2b are not known. Without this information, there is no basis for determining if the approach is correct or if the recession constant is reasonable. Calculated values for sediment yield attributed to road construction and use compare favourably with published values, but a conclusive statement of the sediment yield from road construction cannot be made at this time.

Table 7a. Summary of suspended sediment yields attributed to road construction and other sources (Y_{RCS}), based on expected excess yield minus the mean yield attributed to road use.
$Y_{RCS} = (Y_{obs} - Y_p)*0.82$. Yield Ratio = $(Y_{RCS} + Y_p)/Y_p$

Month	Y_{obs} (Mg)	Y_p (Mg)	Y_{RCS} (Mg)	Effective length of new road (km)	Yield ratio
Sep-97	588.0	62.1	431.2	1.55	7.9
Oct-97	3886.0	458.6	2810.5	0.73	7.1
Nov-97	1085.4	189.5	734.7	0.32	4.9
Dec-97	259.3	89.9	138.9	0.14	2.5
Oct-98	599.2	262.6	275.9	0.33	2.1
Nov-98	362.0	351.2	8.8	0.14	1.0
Dec-98	864.8	624.2	197.3	0.06	1.3
Jan-99	306.6	180.3	103.6	0.03	1.6

Table 7b. Comparison to other results. Total yield from new roads in Catherine Creek is based on expected excess yields, assuming no other source of forest-harvesting-related sediment.

Source	Total length of new road (km)	Density of new road (km/km²)	Total yield from new roads (Mg/km/y)	Mean yield ratio
This study (1997)	1.9	0.04	3.05	5.6
This study (1998)	1.0	0.02	1.42	1.5
Anderson & Potts (1987)	2.5	3.57	0.72	10.0
Megahan et al. (1986)	6.6	1.90	4.79	7.5

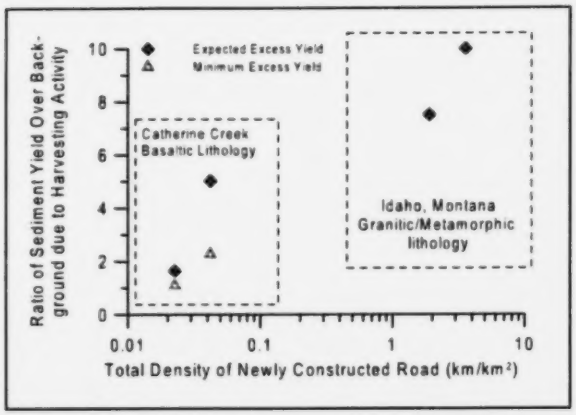
Ratio of Sediment Yield Over Background due to Harvesting Activity
Expected Excess Yield
Minimum Excess Yield
Catherine Creek Basaltic Lithology
Idaho, Montana Granitic/Metamorphic lithology
Total Density of Newly Constructed Road (km/km²)

Figure 16. Comparison of study results regarding the effects of road construction on sediment yield. The ratio based on expected excess yields suggests that there may be an interactive effect between road density and watershed lithology.

Russell Creek: Temporal Changes in Sediment-Production Characteristics

Sediment yield during storms at Russell Creek correlates well with both peak flow and R_{12}; a relationship can be developed to predict yield as a function of either variable, but unlike Catherine Creek, not of both. Regression comparison analysis revealed that there was no significant difference between Periods 1 and 2 in the relationship between sediment yield and R_{12}, but that for Periods 1 and 2 there were parallel relationships between sediment yield and peak flow on Russell Creek (Figure 17). Thus, one equation can be used to describe the relationship between sediment yield and R_{12}, however there is a break in the relationship that occurs at R_{12} of 38 mm (Figure 17, upper graph). This is likely due to the duration of storms of different sizes; the bigger, more intense storms are likely to last longer than the smaller ones. A classification variable D was defined such that if R_{12} was less than 38 mm, the value of D is 1; otherwise, D = 0. Similarly, because there were parallel relationships between yield and peak flow for Periods 1 and 2 (Figure 17, lower graph), another classification variable, P, was used to distinguish the two time periods, such that P = 0 for Period 1, and P = 1 for Period 2. As a result, two equations emerge; storm sediment yield can be expressed as a function of either R_{12} or peak flow, as follows:

$$\ln[Y_S] = 3.68 + 0.144R_{12} + 0.114D \cdot R_{12} - 0.00296D \cdot {R_{12}}^2$$

s.e. = 0.8280, R^2 = 80.3% (9)

$$\ln[Y_S] = 3.18 + 1.23P + 0.425Q_P - 0.0559{Q_P}^2$$

s.e. = 0.8406, R^2 = 80.0% (10)

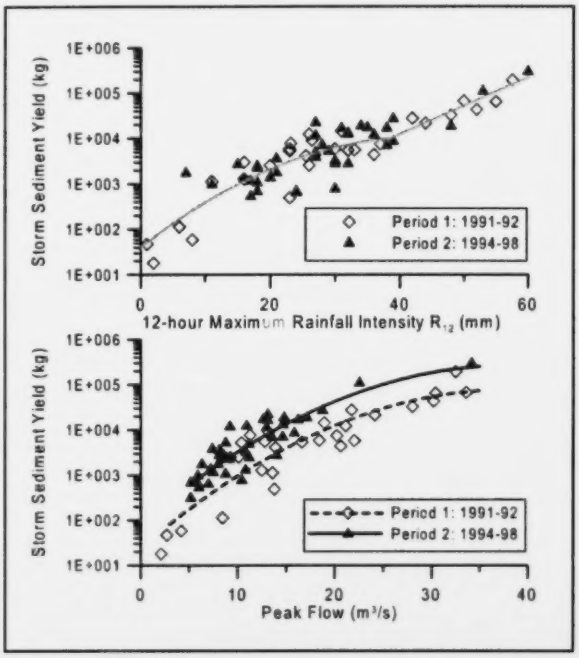

Figure 17. Relationships between storm sediment yield at Russell Creek relative to rainfall intensity (upper graph) and peak flow (lower graph).

Note that there has been no change in the relationship between storm sediment yield and R_{12} during the period from 1991 to 1998 at Russell Creek. However, peak flows have decreased relative to R_{12} (Figure 6), hence sediment yield has increased relative to peak flow. On the other hand, because flow has declined from Period 1 to Period 2, sediment yield would also be expected to decline since yield is calculated as the product of SSC and streamflow, in the absence of any additional sediment sources. Therefore, if yield has really remained unchanged despite a decrease in flow, there must have been new sediment sources created between Periods 1 and 2. Some new roads were built during that interval; in addition, debris flows have occurred in Russell Creek that have most likely altered the sediment budget.

On 24 October 1994 a sidewall failed in a gully in Russell Creek above Stephanie that resulted in a debris flow in that gully. The resultant sediment production followed a pattern similar to that described above for Catherine Creek. At Russell Creek, peak SSC correlates best with R_{12}, for the following relationship:

$$SSC_p = 1.73e^{0.077R_{12}}$$

R^2 = 64.1% (11)

As with Catherine Creek, the peak SSC of the 24 October event lies well above the 90% prediction limit of Equation 9 (Figure 18).

This event produced the highest measured SSC in Russell Creek to date. The probable sediment hydrograph that would have occurred in the absence of the debris flow (Figure 19) was reconstructed using the same method as that described for Catherine Creek. Using a relationship between SSC and streamflow, an abrupt discontinuity in the relationship on the rising limb identifies when the sediment from the debris flow began to affect the main gauging site. Other events had similar characteristics (e.g., 7 April 1996, Figure 20), leading to the supposition that they also involved some kind of episodic sediment input. For these two events, the ratio of observed sediment yield over the simulated yield with the landslide effect removed is 1.75 (Table 5). This is consistent with the mass-wasting effect for Catherine Creek, since buffering by the valley flat is a mitigating factor at Russell Creek.

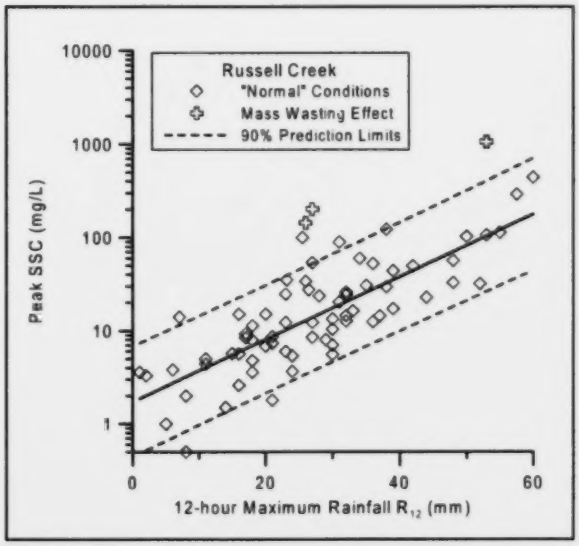

Figure 18. Relationship between peak SSC and rainfall intensity at Russell Creek.

Comparison of Temporal Variability Between Russell and Catherine Creeks

Another way to look at changes in sediment yield at Russell Creek is in relation to Catherine Creek. Because Periods 1 and 2a on Catherine Creek are not significantly different, Catherine Creek can be used as a pseudo-control to assess changes in sediment yield on Russell Creek from Period 1 to 2, by excluding data from Period 2b (Figure 21). For this analysis, paired events on Russell and Catherine Creeks were used. A regression equation for Period 1 was developed, as follows:

$$Y_{Russ} = 0.7342 \cdot Y_{Cath}^{0.896}$$

s.e. = 2705, R^2 = 86.7% (12)

As in the above analysis, a 95% prediction interval was also calculated. Six of the 17 paired events in Period 2a fall below the lower prediction limit, indicating a significant decrease in sediment yield from Russell Creek between Periods 1 and 2. An additional four events fall just above the lower prediction limit. This suggests that overall, there has been a decrease in sediment yield at Russell Creek from Period 1 to Period 2. That decrease is marginally significant relative to sediment yields for paired events on Catherine Creek, based on the assumption that sediment yields for Period 2a on Catherine Creek are not

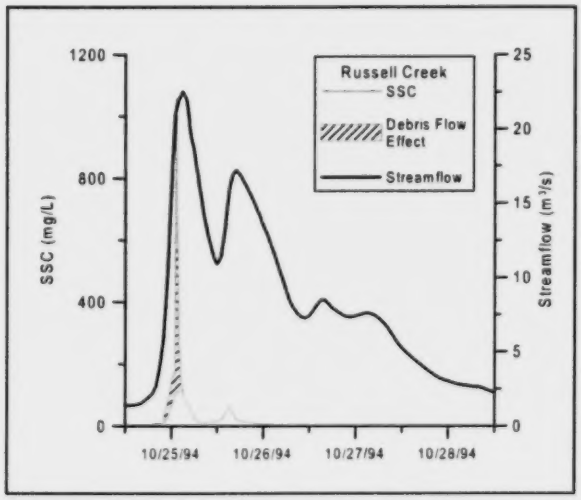

Figure 19. Russell Creek streamflow and SSC, 24 October 1994 event.

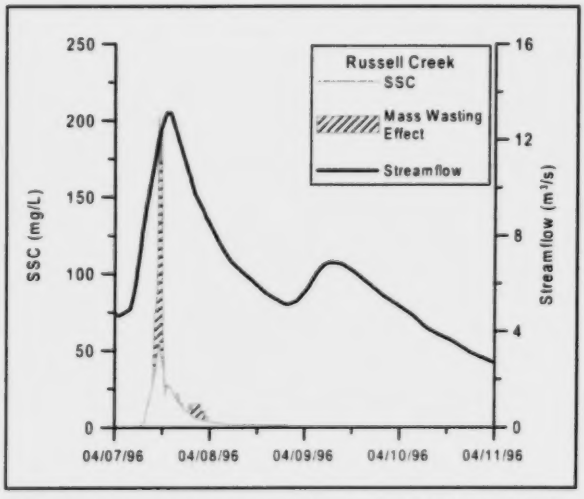

Figure 20. Russell Creek streamflow and SSC, 07 April 1996 event.

significantly different from those of Period 1. For Period 2a, the average decrease in sediment yields from Russell Creek relative to those from Period 1 is about 54%, depending on whether the percent change is weighted according to the mean yield or not.

During Period 1, the ratio of sediment yield from Catherine vs. Russell Creek is 4.7 (Table 8). If Period 1 sediment yields from Russell Creek are adjusted to account for the change in yield as described above, then the ratio of sediment yields from Catherine Creek over Russell Creek for Period 1 becomes 10.6. For Period 2b, that ratio jumps to 71. This indicates a 670% increase in sediment yield from Catherine Creek during Period 2b, relative to adjusted yields from Russell Creek. For Period 2a, the ratio is 18.9, which is consistent with slightly elevated yields due to lighter road activity during the fall of 1998 compared with the fall of 1997.

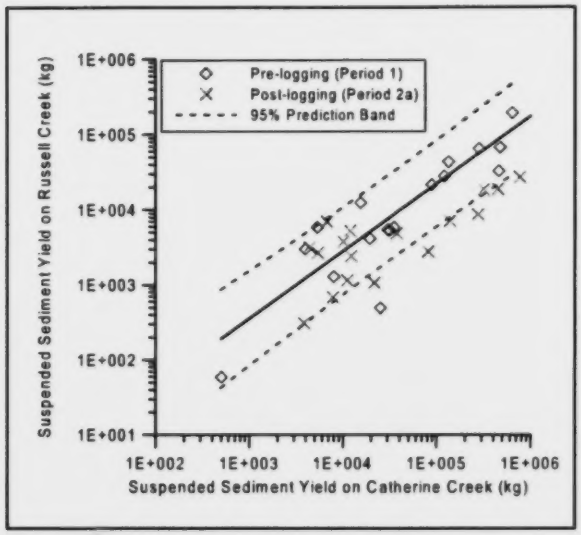

Figure 21. Relationship between storm-based sediment yields for paired events on Russell Creek relative to Catherine Creek.

As a comparison to the above examples, streamflow and SSC hydrographs for the 30 September to 3 October 1997 at Russell and Stephanie Creeks are presented (Figures 22 and 23). These are directly comparable to the same event as it occurred at Catherine Creek (Figure 11). Note the differences in the scale of the axes depicting SSC. Russell and Stephanie Creeks experienced higher peak flows in the 30 September event, contrary to the event sequence at Catherine Creek. Despite similar lithology, Catherine Creek experienced SSC levels far in excess of those measured at Stephanie Creek due to the road construction and use effect at Catherine Creek. SSC levels at Stephanie compare better to those that occurred on 20 November 1998 at Catherine Creek (Figure 13), after road construction and use had stopped for the season. SSC levels at Russell Creek are greatly reduced compared to Stephanie Creek, due to a combination of valley flat buffering from Russell above Stephanie and the dilution of sediment-laden flows from Stephanie Creek. However, SSC levels at Russell Creek on 30 September 1997 are comparable to the SSC levels for the 24 October 1994 event, simulated to remove the effect of the debris flow (Figure 19).

Sub-Basins of Russell Creek vs. Catherine Creek: Relative Roles of Lithology and Harvesting on Sediment Production

The roles of lithology, basin morphology, and harvesting development on sediment production can be investigated by com-

Table 8. Total storm sediment yields at Russell and Catherine Creeks for paired events, Periods 1 and 2.

Period	Paired events (no.)	Total yield: Russell Creek (kg)	Total yield: Catherine Creek (kg)	Ratio of Catherine yield to Russell yield	Russell yield adjusted to Period 2 (kg)	Ratio of Catherine yields to adjusted Russell yields
1. 1991-92 (pre-harvesting)	17	49 6608	2 381 252	4.8	224 467	10.6
2. 2a (post-harvesting)	17	115 175	2 173 364	18.9	115 175	18.9
3. 2b (post-harvesting)	10	77 794	5 526 175	71.0	77 794	71.0

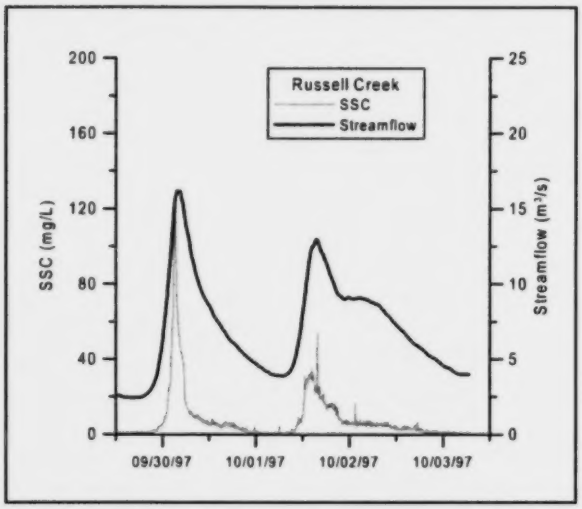

Figure 22. Russell Creek streamflow and SSC, 30 September and 01 October 1997 events.

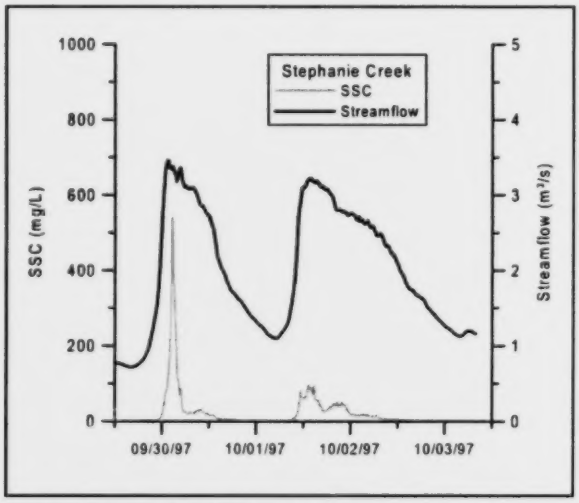

Figure 23. Stephanie Creek streamflow and SSC, 30 September and 01 October 1997 events. Note the different scales between this graph and Figures 22 and 11.

paring storm-based sediment yields at the various stream gauge sites. In order to compare these sediment yields, both the yields and the peak flows were expressed on a unit area basis. As in the above analyses, a combination of regression comparison, stepwise regression, and best-subsets regression analysis was used to generate final regression equations to describe suspended sediment yield as a function of peak flow and rainfall variables; in all cases, the best rainfall variable was R_{24}. The analysis was done for Stephanie Creek, Russell Creek above Stephanie Confluence, lower Russell Creek (below the Confluence), and Catherine Creek (Figures 24, 25, upper graphs).

Sediment-yield relationships may be affected by lithology, channel gradient, and sediment source connectivity. Catherine Creek is underlain entirely by basaltic bedrock, and sediment sources are directly connected to the channel network. The basaltic bedrock type dominates Stephanie Creek and Russell Creek above Stephanie, whereas lower Russell is underlain by the granitic lithology. Sediment sources at Stephanie and lower Russell Creek are directly connected to the channel network, whereas Russell Creek above Stephanie is buffered from hillside sediment sources by a valley flat that absorbs a proportion of the sediment before it reaches the main channel (Hudson 2001). The effect of channel gradient on storm sediment yield was also tested by dividing yields at each site by the mean gradient of the lower channel reach immediately above each gauge. Sediment yields and yields normalized by gradient were analyzed separately. Visually, this normalization has a small effect on the relationship between specific yield and either R_{24} or specific peak flow. Yields at Stephanie Creek appear to be slightly higher than at Catherine Creek for a given specific peak flow, but when divided by the channel gradient they appear to be the same.

Regression comparison revealed that regression equations for Stephanie and Catherine Creeks are colinear. Therefore, data from those sites can be combined to form a single equation. Regression equations for this combined data set were found to be parallel to those of Russell Creek above Stephanie for both the specific yields, and the gradient-normalized specific yields. Therefore, a single regression equation for yield can be used to represent all three sites, using a dummy variable to account for the site, as follows:

$$\ln(y_s) = 1.2 + 7.25q_p + 0.000445R_{24}{}^2 - 0.0484R_{24}q_p + 1.90Site$$

(R^2 = 84.3%, s.e. = 0.7274) (13)

where

y_s is the specific sediment yield (kg/km²),

q_p is the specific peak flow (m³/s/km²), and

Site is a classification variable that is equal to 1 for Stephanie and Catherine Creeks, or 0 for Russell Creek above Stephanie Confluence.

The thing that all these sites have in common is dominance by the basaltic Karmutsen formation; the regression equation for lower Russell is significantly different from the equations for the other sites, as follows:

$$\ln(y_s) = 2.05 + 3.68q_p + 0.0210R_{24} + 0.662D$$

(R^2 = 83.6%, s.e. = 0.7514) (14)

where

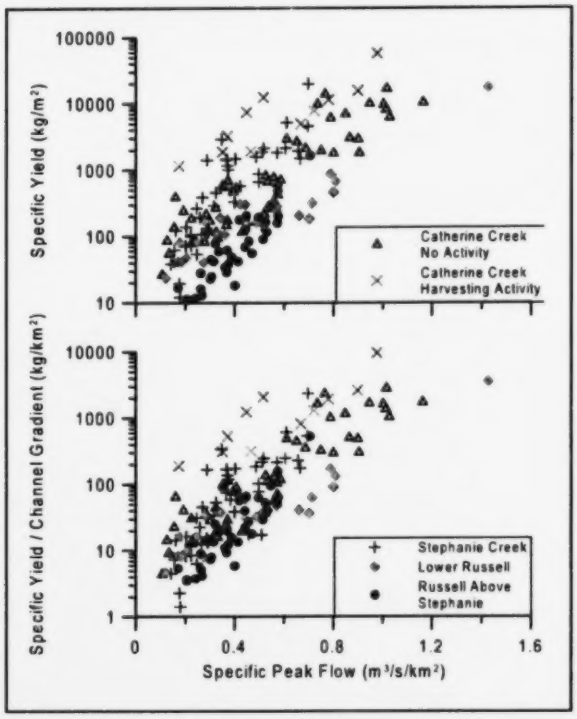

Figure 24. Specific yield vs. peak flow for Catherine Creek and Russell sub-basins

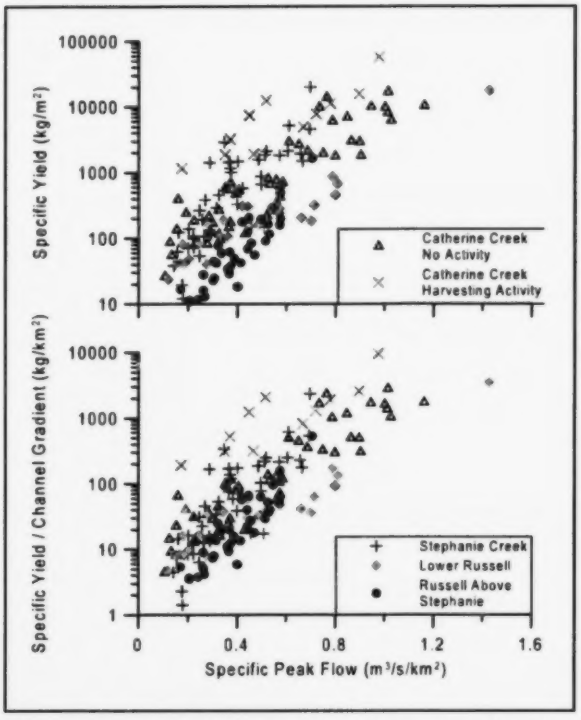

Figure 25. Specific yield vs. rainfall intensity for Catherine Creek and Russell sub-basins.

D is a dummy variable that represents event size,

D = 1 for small events (q_p <0.6), and

0 for large events.

Note that this is essentially the same dummy variable used previously to account for the break in the relationship between yield and R_{12} for Russell Creek (Equation 9). If R_{12} = 38 mm, then R_{24} ~ 49 mm, which equates to a peak flow of around 0.6 $m^3/s/km^2$.

If the same analysis is done with the sediment yields normalized for channel gradient (Figures 24, 25, lower graphs), the regression equations for Stephanie, Catherine and Russell above Stephanie, and for lower Russell are as follows (Equations 15 and 16 respectively):

$$\ln(y_s / G) = 7.31 q_p + 0.000407 R_{24}^2 - 0.0429 R_{24} q_p + 1.07 Site$$

(R^2 = 97.3%, s.e. = 0.7154) (15)

$$\ln(y_s / G) = 4.25 q_p + 0.0197 R_{24} + 0.965 D$$

(R^2 = 99.1%, s.e. = 0.3848) (16)

where

y_s/G is the normalized yield, that is, the storm suspended-sediment yield divided by the mean gradient of the channel above the gauge.

The rainfall and peak flow coefficients are similar to those of Equations 13 and 14, but the intercepts are not significant and the classification variable coefficients are different, suggesting that channel gradient has an effect on the mean sediment yields.

To detect significant differences among the sediment yields at the different sites, an ANOVA approach was used. Events were divided into two classes: small and large, based on the criterion already established for Russell Creek. That is, a small event is one in which the R_{24} is less than 50 mm, a large event has R_{24} of greater than or equal to 50 mm. The treatments consist of:

- Stephanie and Catherine Creeks, representing the basaltic bedrock with directly connected sediment sources. The yields from Period 2b at Catherine Creek are not included in order to exclude the effects of road activity.
- Russell Creek above Stephanie, representing basaltic bedrock with the sediment sources disconnected from the channel due to the valley flat.

- Lower Russell, representing igneous bedrock with directly connected sediment sources, and a negligible road effect.

The ANOVA model tested the effects of treatment, storm size, and the interaction between the effects. Because the design is unbalanced (unequal number of observations per cell), GLM was used (Minitab Inc. 1995). Not surprisingly, the storm size and treatment effects were both significant, although the interaction between effects was not, suggesting that the differences between treatments were consistent from small to large events. In other words, if yield at Site A is less than yield at Site B for small events, the same is true for large events. To detect where the significant differences lie, two-sample t-tests were used. Comparisons were made between sites by event size. Results of these comparisons are summarized (Table 9).

Using Equations 13 and 14, the relative roles of bedrock lithology and sediment source connectivity can be reconstructed. To do this, the storm data from all sites (Table 3a, 3b) were lumped together. As before, the storms were classified as large or small, and yields were calculated. Average storm sediment yield was calculated by storm size for each morphological type (Table 10). To assess the effect of channel gradient on sediment yield, normalized yields were calculated, and converted to actual yields by multiplying the normalized yields by the channel gradient at each site. For this analysis, Stephanie Creek and Catherine Creek data were separated, and the calculations were performed separately on data that pertained to each site. Then, the per-cent difference between the yields calculated by Equations 13/14 and Equations 15/16 were determined (Table 11). These differences represent the effect of channel gradient on the sediment yield during storms.

DISCUSSION

Using the results presented above, the relative importance of watershed lithology, morphology, and forestry-related development can be quantified (Table 12).

The role of lithology can be assessed by comparing the basaltic-connected type to the igneous-connected type (Table 10). For small and large events, the ratios of the average sediment yields (in kg/km^2/storm) are 3.4 and 7.1 respectively, with an average ratio for all storms regardless of size of 5.9. This is consistent with earlier findings (Hudson and Sterling 1998). Thus, the sediment yield from the basaltic bedrock type per unit area is about six times (or 600%) that of the granitic bedrock type, and is also positively related to storm size. Stephanie Creek contains 70% basaltic bedrock or basaltic surficial material over granite compared to Catherine Creek with 100% basaltic lithology. However, there was no significant difference between Stephanie and Catherine Creeks in terms of yield relationships due to the dominance of the basaltic lithology over the granitic lithology. It has been noted that two large features within the basaltic lithology dominate the sediment budget of Stephanie Creek (Hudson 2001).

The role of sediment source connectivity can be assessed by comparing the basaltic-connected to the basaltic-buffered types.

Table 9. Results of t-tests comparing lithological/morphological types. The body of the table lists the t-score, the associated probability, and the significance (S = significantly different means, N = means not significantly different).

Type	Event size	Basaltic buffered	Igneous connected
Basaltic connected	Small	7.25, 0.0000 (S)	3.14, 0.0014 (S)
	Large	4.65, 0.0004 (S)	1.43, 0.1000 (?)
Basaltic buffered	Small		-3.85, 0.0005 (S)
	Large		-1.26, 0.2500 (N)

Table 10. Average storm sediment yield (kg/km^2/storm) by lithological/morphological type, excluding Period 2b at Catherine Creek.

Event size	Basaltic connected	Basaltic buffered	Igneous connected
Small	551.1	82.4	163.1
Large	5748.0	859.7	813.6
Average	2064.1	308.7	352.5

Table 11. The effect of channel gradient on sediment yield.

Sub-basin	Event size	Mean yield: Equations 10/11 (kg/km^2/storm)	Mean yield: Equations 12/13 (kg/km^2/storm)	% change
Stephanie	Small	336.8	412.0	22.3
Catherine	Small	881.5	805.3	8.7
Lower Russell	Small	163.1	185.5	13.7
Confluence	Small	82.4	83.4	1.2
Stephanie	Large	1652.7	1935.6	17.1
Catherine	Large	5306.3	5248.4	1.1
Lower Russ	Large	813.6	882.4	8.5
Confluence	Large	859.7	1031.3	20.0

Table 12. Summary of the effects of various factors on storm sediment yield. The ratios represent the average sediment yield during storms for the first situation over that of the second situation described under the comparison. Thus, the factors presented are ranked in order of importance in their control over sediment production.

Factor	Comparison	Ratio
Forest harvesting activity on basaltic terrain	Sediment yields, forest harvesting activity vs. non-activity periods.	7.7
Connectivity	Connected basaltic type vs. buffered basaltic type.	6.6
Lithology	Basaltic vs. igneous bedrock type.	6.0
Episodic mass wasting	Measured yield with mass-wasting effect minus simulated background.	1.75-2.5
Change in ECA	Mean Yields at Russell Creek 1992-93 vs. 1994-98.	2.1
Roads and road use	Sediment-budget research at Russell Creek, non-use roads; inferred contribution from road use, Catherine Creek.	1.1-1.5
Channel gradient	Comparison of equation with and without channel gradient as a factor.	1.1

In this case the ratio of average sediment yield from the connected relative to the buffered type is 6.7, regardless of storm size. Russell Creek above Stephanie is dominated by the basaltic lithology at 73% of its area. Therefore, if it was not buffered by a valley flat, it would be expected to possess sediment yield characteristics similar to Stephanie Creek. Thus, the valley flat that buffers the channel of Russell Creek above Stephanie has a slightly stronger control on sediment yields than lithology.

Established roads in Catherine Creek, when not used for active hauling, do not have a significant effect on sediment production. The contribution of roads to the sediment budget of Russell Creek has been described by Hudson (2001). The relationships between storm-sediment yield and peak flow and rainfall intensity for Catherine Creek are somewhat more "noisy" than those of Russell Creek. The noise in those relationships and the fact that sediment yield during storms at Catherine Creek is about five times that of Russell Creek masks any contribution from roads during non-use periods. The large increase in sediment yield at Catherine Creek that occurred in the fall of 1997 and again to a lesser extent in the fall of 1998 corresponds to periods of activity in the watershed, and is therefore most likely related to forest harvesting. It is likely that road construction and use contributed to this increased yield, but there is uncertainty regarding the exact source of the sediment. Because the sediment source inventory for Catherine Creek is incomplete, it is not possible to determine the cause of the increased yield at this time. Some possible causes include landslides associated with new roads, destabilization of debris flow scars, and stream bank erosion in the upper watershed.

The apparent effects of forest harvesting activity in Catherine Creek increased yield up to 7.7 times higher than background levels. This order-of-magnitude increase in sediment yield is the largest influence on sediment yield among the factors tested, and is more likely related to the inherently unstable nature of the basaltic terrain.

The effect of episodic mass-wasting events on sediment production was less than expected. At Catherine Creek, landslides into the creek increased the sediment yield an average of 2.5 times higher than background levels, while at Russell Creek the increase due to connected mass wasting was 1.75 times higher than background levels. Two of the events are known to have involved mass wasting; both were harvesting related. The other events that were analyzed were assumed to involve mass wasting because they had characteristics consistent with the known events. Harvesting related landslides are normally smaller than naturally occurring events; however, the event of 19 November 1991 at Catherine Creek most likely involved a naturally occurring landslide. None of the evidence suggests that the effects of individual landslides directly into the channel last beyond the event in which they occur. However, at Catherine Creek the high background sediment production reflects the cumulative effect of sediment added to the channel system by many such events over time.

Because sediment yields from Catherine Creek during periods of non-activity are not significantly different from those of the pre-treatment period, it is clear that the presence of clearcut blocks in a watershed does not directly affect sediment production. This has been corroborated by others (e.g., Megahan et. al. 1995). However, an indirect relationship exists between clearcut harvesting and sediment yield in that harvesting increases streamflow, which in turn results in higher sediment yields. This was shown by Beschta (1978), and results presented here suggest that this may also be the case at Russell Creek. However, this was not shown conclusively. A reduction in ECA from 21% in 1992 to 15% in 1998 resulted in a reduction in sediment yield of 55% relative to Catherine Creek. Conversely, sediment yields were 110% higher in 1992 than in 1998 due to increased streamflow based on a relationship with Catherine Creek. On the other hand, based on a relationship of yield vs. rainfall intensity at Russell Creek, there was no difference between Period 1 and Period 2 yields. Because there were additional sediment sources added to the watershed in the intervening period, this may account for the apparent discrepancy between the results of the two different methods. The effect of further reduction in ECA as regeneration continues cannot be assessed at this time.

The effect of channel gradient on sediment production is a relatively minor factor controlling sediment production. The channel gradients represented by the gauging sites are in the range of 3–8.5%. In that range, the average difference in sediment yield—depending on whether or not channel gradient was taken into account—was 11.6%.

Implications for Forest Management

The results of this study provide some important insights into watershed assessment and how to interpret Coastal Watershed Assessment Procedure (CWAP) data (BCMOF and BCMOE 1999), as well as some important forest-management implications regarding roads on highly erodibe bedrock types.

We expected to find that episodic mass-wasting events that entered the channels would be the largest sources of sediment measured at the gauging sites. However, this turned out not to be the case. Other factors related to forest-harvesting activity on the basaltic Karmutsen lithology, in the absence of a valley flat to buffer the channel, had by far the largest effect on sediment production. Order-of-magnitude increases in sediment yield as a result of road construction have been observed elsewhere (Anderson and Potts 1987; Megahan et al. 1986). Because the increase in yield over background levels is correlated with the effective length of new road, this implies that road construction and use is at least partly responsible for the increased yield. Future research at Catherine Creek is required in order to determine additional factors which may be responsible for the observed effect of forest harvesting on sediment yield.

Horel (1997) interpreted the risk of surface erosion from roads at Catherine Creek as low and at Russell Creek as moderate, based on measured road densities. This was a correct interpretation of the data, based on the state of knowledge at that time. The erosion risk from roads in Russell Creek should probably be rated as low due to the buffering effect of the valley flat. An interaction occurs between the road density and the lithology and connectivity of the terrain where the roads are located. Correct interpretation of CWAP hazard indices should include an assessment of these factors, since they are clearly more important factors than forest development alone. Results show that while the risk of sedimentation from established roads in Catherine Creek may indeed be low, it is clear that something happened in the course of normal forest-harvesting activities that resulted in a dramatic increase in sediment yield. While the cause of the increase is unclear at this time, these results suggest that the effects of proposed activity in a watershed with inherently unstable terrain may be quite different from the effects of past development. If this proves to be the case, then this would imply that a different set of hazard indices should be developed to assess the probable effects of future development on sediment budgets.

The interaction between ECA and peak streamflow and its subsequent effect on sediment yield should be noted, although this was not shown conclusively. Study results suggest that a reduction in ECA of only about 4% may have resulted in a reduction in sediment yield of 55%, an effect that is comparable to the effect of episodic mass-wasting events on sediment production. It should be noted that the ECA effect applies to all sediment-production events, whereas the mass-wasting effect applies only to rare events. Future research in Russell Creek will attempt to resolve the ECA effect more conclusively.

CONCLUSIONS

Since the early 1990s, the Vancouver Forest Region of the BC Ministry of Forests has conducted research on the sediment budgets of forest streams in the Tsitika River watershed, on northeastern Vancouver Island in Coastal British Columbia. One aspect of the research involved a comparative analysis of the sediment-production characteristics of two sub-basins—Catherine Creek and Russell Creek—from November 1991 to December 1998.

The analysis found that the main factors affecting sediment production in Catherine and Russell Creeks, Tsitika River watershed include (in order of importance): forest-harvesting activity on basaltic bedrock, connectivity of sediment sources to the channel system, bedrock lithology, changes in streamflow as a result of changing ECA, and episodic mass wasting. Results of the analysis provide some insight into the roles of various factors, including forestry-related activities, in controlling production and transport of suspended sediment in forest streams.

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APPENDIX A:

INTERPRETATION OF TURBIDITY AND SSC DATA

The process of sediment production in high-energy Coastal streams is extremely complex. Consequently, interpretation of suspended sediment and turbidity data is also very complex, and has been described in detail by Hudson (2001a). Relationships between turbidity and suspended sediment depend on grain-size distribution. The grain-size distribution of the suspended sediment in streams in turn depends on sediment supply and hydrologic conditions. Therefore, at any given site, more than one relationship exists between turbidity and suspended sediment. This results in various suspended sediment regimes.

A sediment-production regime is defined as a specific range of conditions that control the relationship between suspended sediment concentration (SSC) and turbidity at a point on a stream. The relationship that is usually in effect is called the normal regime (Figure A!). The relationships are curves because as in-stream flow conditions and turbidity change, the grain-size distribution of the suspended sediment also changes. At low turbidity the normal regime consists entirely of fines (i.e., silt and clay). At higher flows (and hence, at higher turbidity) the stream is capable of carrying sand as well as fines, and the proportion of sand in the suspended load increases with increasing turbidity. During a large storm, sediment production will switch to a coarser regime. Under the coarse regime, the stream carries either a coarser grade or a higher proportion of sand for a given turbidity, resulting in a steeper SSC vs. turbidity curve. After large storms, the sediment production switches to a finer regime. This transition occurs because the supply of transportable sand is more limited than the supply of fines, and large storms have a tendency to flush most of the available sand from the watershed. Subsequent to this, the finer regime will remain in effect until erosional processes have made available a fresh supply of transportable sand, and until storms occur that are capable of transporting it.

The grain-size distribution of the suspended load was determined by calibrating the OBS probes in a calibration column using graded stream channel sediment, and comparing the resultant calibrations to the field calibration curves (Hudson 2001a). At Russell Creek, the normal regime consists entirely of fines at turbidities below 40 NTU, whereas Catherine Creek carries a proportion of sand in suspension at all turbidity levels under the normal regime. The fact that the SSC vs. turbidity relationship for the normal regime at Catherine Creek has a steeper slope than that of Russell Creek reflects the fact that Catherine Creek not only carries a greater proportion of sand than Russell Creek, but that the sand is also of a coarser grade (Figure A1). While Russell Creek carries sediment in the clay to very fine sand range, the very coarse regime at Catherine Creek is dominated by medium sand. This is a direct result of the fact that Catherine Creek has a steeper gradient than Russell Creek, and also has substantially more sand stored in the channel. This is consistent with the findings of Duncan and Ward (1985), and reflects the fact that basaltic rock is more easily broken down by mechanical weathering processes than granitic rock.

A closer examination of the SSC vs. turbidity relationship the normal regime at Catherine Creek reveals that a change has occurred in the normal regime between the 1991–1992 calibration and the 1997–1998 calibration, indicating that there has been a change in grain-size distribution of suspended sediment (Figure A2). These two periods represent pre-harvesting and post-harvesting (or ongoing development) periods. In comparison with the lab calibration line for fines (i.e., silt and clay), it is clear that the post-harvesting normal regime suspended-sediment load contains more fines than the pre-harvesting condition.

Regime transitions at Russell Creek occur in response to rainfall intensity threshold at a proportion of the peak flow (Hudson 2001a). At Catherine Creek, the transition from normal to coarse and very coarse regimes occurred during monthly peak flow events during the fall. Because the sediment is mostly stored in the channel system at Catherine Creek, that sediment is entrained by the flow as the stage rises. Thus, the largest flow that occurs in any month tends to remove most of the available sand. Subsequent events within a month of each monthly peak flow do not attain a stage high enough to reach transportable sand higher up on the channel banks, and consequently the transition from normal to coarse regime does not occur. Apparently, about a month is needed for the supply of transportable sand to be replenished by erosional processes. Like Russell Creek, the transition from normal to coarse regime occurs at about 80% of the peak flow. Early season events prior to the first big peak flow also tended to involve regime transitions, because at that time the supply of transportable sand is still plentiful. In contrast, flow events from January to March tended to be supply limited. This is most likely due to snow conditions, which tend to suppress sediment production.

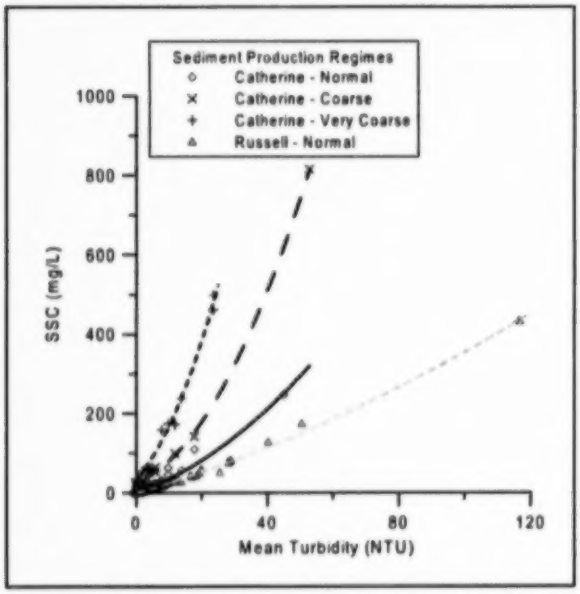

Figure A1. Relationships between SSC and turbidity for different sediment production regimes, Catherine and Russell Creeks.

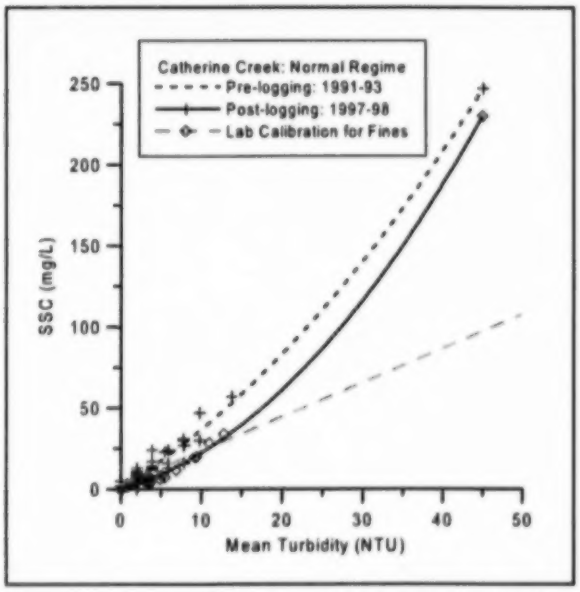

Figure A2. Changes in the normal regime SSC vs. turbidity relationship at Catherine Creek.